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Spatial interpretation of high-resolution environmental proxy data of the Middle Pleistocene Palaeolithic faunal kill site Schöningen 13 II-4, Germany

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To spatially characterize the palaeolakeshore environment at the archaeological kill site Schöningen 13 II-4 of the Middle Pleistocene Reinsdorf sequence, in-depth palynological, geochemical, aquatic microfossil and archaeological analyses were undertaken on sediment sections with an average thickness of about 15 cm, concordantly overlain by faunal remains, dominated by horse, from the unique 'Spear Horizon' layers of the 1995 excavation campaign. The data reveal a distinctive lake level drop, documented by the change from a carbonate-rich lake marl to a carbonate-free organic mud with increased carbon content and decreasing C/N, Si/Al, Si/K and Fe/Al ratios, indicating a higher pedogenic supply of organic matter and drier conditions at the site. Compared with older, similar transitional phases of lake level changes occurring within the Reinsdorf sequence, it is important that these youngest sediments are undisturbed, indicating continuous development. Ostracod and diatom analyses indicate a lowering water level with higher salinities and rich aquatic vegetation. Mesorheophilic ostracod species along with tychoplanktic diatom taxa point to flowing waters and turbulence at the lakeshore, presumably related to spring-fed streams originating from nearby highlands. Palynological results reveal a very diverse zonal vegetation pattern around the palaeolakeshore considering an area of investigation of approximately 50 × 75 m and a tessellated type of regional vegetation during the formation of the archaeological horizons. On topographically lower elevated areas, birch groves and taxa favouring wet, marshy conditions such as Cyperaceae, indicative of terrestrialization, were predominating, while other stands of this transitional phase reveal a very dry, grass-dominated steppe woodland favouring a rich wildlife with a striking number of megaherbivores. Our results suggest that the lithological differences of the 'Spear Horizon' layers containing the archaeological finds were due to their respective topographical situation and that the layers were deposited almost simultaneously during the beginning of the lake level drop. Human activities seem to have concentrated in sparsely vegetated areas along the palaeolakeshore, rather than in areas of adjacent denser birch swamp forest stands.

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The open-cast lignite mine Schöningen in northeastern Lower Saxony, Germany (Fig. 1A), is well known for its outstanding archives of Pleistocene flora and fauna, climate and human evolution and for the worldwide oldest Palaeolithic wooden hunting weapons in particular (Thieme 1997; Mania & Mai 2001; Urban 2007a, b; van Kolfschoten 2014; Böhme 2015; Urban & Bigga 2015; Serangeli *et al.* 2018; Conard *et al.* 2020; García-Moreno *et al.* 2021; Krahn *et al.* 2021; Tucci *et al.* 2021). Schöningen is situated about 100 km east of Hanover at the south-eastern edge of the Muschelkalk limestone ridge of the Elm (Fig. 1A). The Eocene lignite seams in the area of Schöningen formed in the western rim syncline of the Helmstedt-Staßfurt salt dome and are overlain by 45-m-thick Quaternary deposits (Fig. 1B).

The well-preserved weapons were found in the lacustrine sediments of the Middle Pleistocene Reinsdorf sequence between Elsterian and Saalian glacial deposits (Urban 1995; Tucci *et al.* 2021). Mania (1998, 2007a, b) proposed a model of six superimposed sequences of climatically induced large-scale fluvial erosional channels (I–VI), overlying the Elsterian till. Older interglacial deposits unconformably overlying Elsterian till and meltwater deposits were assigned to the Holsteinian interglacial (channel I) (Fig. 1B) (Urban *et al.* 1991). Based on palaeobiological and chronometric data from

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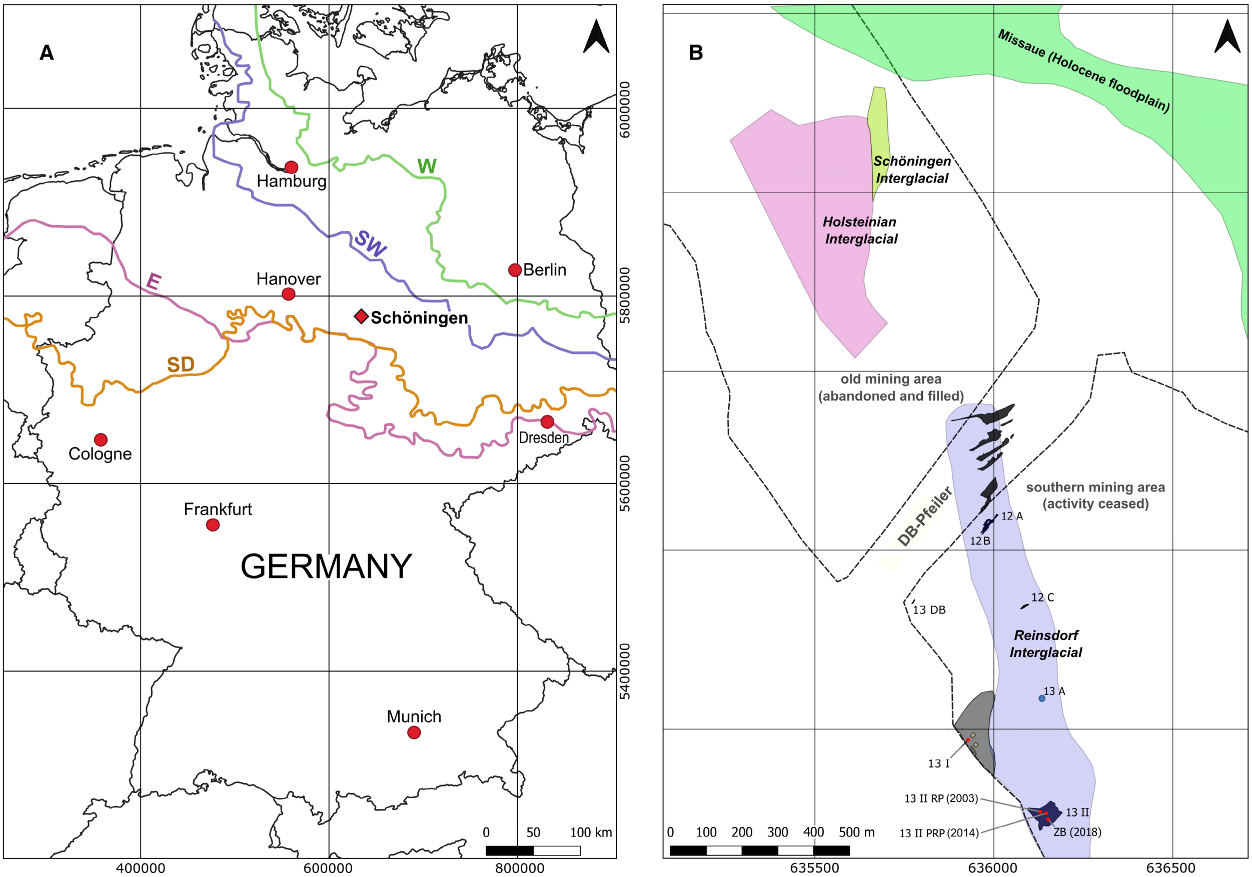


Fig. 1. A. Location of Schöningen (northern Germany) and maximum extent of ice sheets (coloured lines: Elsterian (E), Saalian Drenthe Stage (SD), Saalian Warthe Stage (SW) and Weichselian (W)). B. Map of the northern (worked out and filled) and southern mining area (mining activity ceased) and important archaeological sites and sequences (modified after Urban & Bigga 2015; original map by U. Böhner, Niedersächsisches Landesamt für Denkmalpflege (NLD), Hanover).

the archaeological sites Schöningen 12 and 13 II, the Reinsdorf interglacial sequence (channel II) (Fig. 1B) was tentatively correlated with Marine Isotope Stage 9 (Urban *et al*. 2011, 2023; van Kolfschoten 2012, 2014; Sierralta *et al*. 2012, 2017; Richter & Krbetschek 2015; van Kolfschoten *et al*. 2015a, b; Kunz *et al*. 2017; Tucci *et al*. 2021). At the archaeological find complex 13 II five lithologically clearly distinguishable units, 13 II-1 to 13 II-5, were defined at the Reference Profile (RP) of 2003 (Thieme 2007a, b) reflecting lake-level fluctuations resulting from climate and vegetation changes (Urban & Bigga 2015; Krahn *et al*. 2021; Tucci *et al*. 2021). The archaeological site Schöningen 13 II level 4, the ‘Spear Horizon’, consists of a small lithic collection and numerous faunal and plant remains (Thieme 2005; van Kolfschoten 2014; Conard *et al*. 2015; van Kolfschoten *et al*. 2015a, b; Serangeli & Conard 2015; Urban & Bigga 2015).

The archaeological assemblage from the ‘Spear Horizon’ follows an evident spatial pattern (Böhner *et al*. 2015). Different lines of evidence, including the orientation of finds (Peters & van Kolfschoten 2020; García-Moreno *et al*. 2021), the taphonomy of faunal remains (Turner *et al*. 2018; Hutson *et al*. 2020), the spatial patterning of the assemblage (Böhner *et al*. 2015; Peters & van Kolfschoten 2020; García-Moreno *et al*. 2021) and micromorphology analysis (Stahlschmidt *et al*. 2015), indicate that high-energy processes were not involved in the formation history of the site and, therefore, the assemblage was found in ‘primary position’ and yields potential for analysing the spatial traces of human activity. This paper intends to reconstruct local and regional vegetation patterns and analyse local depositional differences in time and distribution regarding the excavated faunal remains by high-resolution pollen and aquatic microfossils, sedimentological and geochemical analyses of the original find-bearing sediments of units Schöningen 13 II-4c and II-4bc/ab/b of the ‘Spear Horizon’.

Material and methods

Material

The sediment blocks come from the excavation campaign in 1995 when the famous wooden spears were discovered

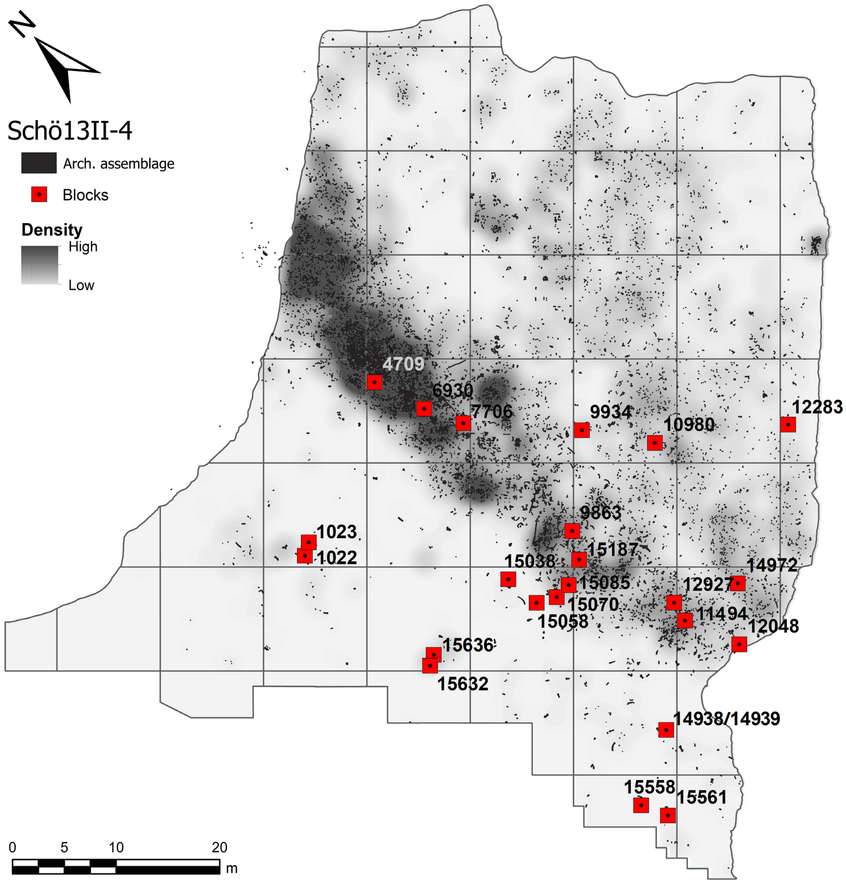


Fig. 2. Map of Schöningen 13 II-4 'Spear Horizon' showing the spatial distribution of the archaeological assemblage, compared with the location of the sampled blocks mentioned in the text. The background represents the Kernel density of finds (A. García-Moreno; original plans by U. Böhner, Niedersächsisches Landesamt für Denkmalpflege-NLD).

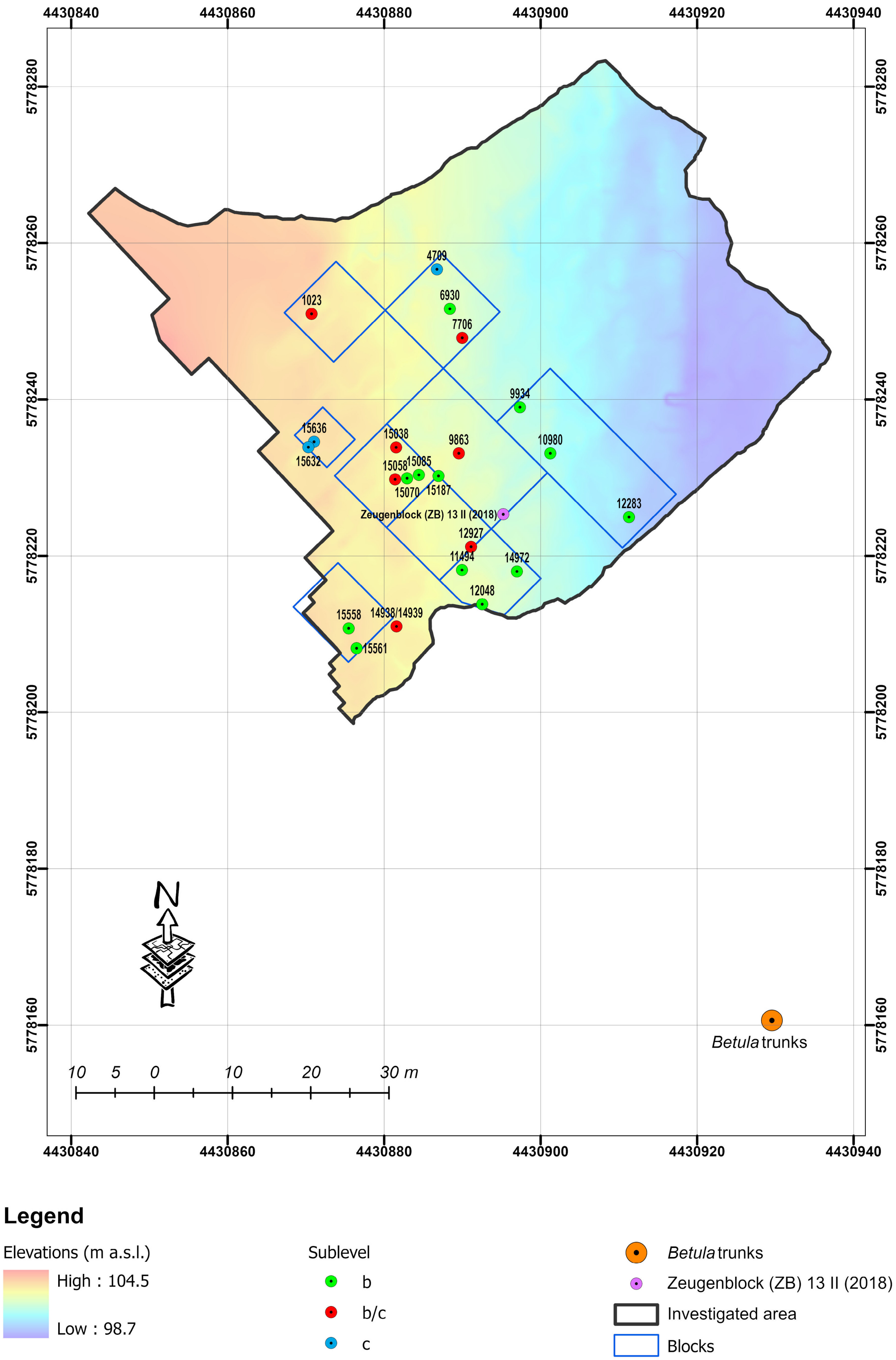
together with numerous remains of large mammals, representing the hunted game (Thieme 1997) (Fig. 2). Blocks with faunal remains overlying lacustrine sediments were then taken and kept in wooden boxes or in gypsum cladding and interim stored in a storehouse freezer for future analysis. Between 2014 and 2016 the intact blocks were brought to the laboratories of the Niedersächsisches Landesamt für Denkmalpflege, Hanover and the paläon-research museum, Schöningen for archaeozoological, sedimentological, palynological and aquatic microfossil sampling.

The identification number (ID) of each archaeological find is used also for the corresponding block (Fig. 2). The areas (1–9), local coordinates, elevation and lithological description of archaeological site Schöningen 13 II, layers 13 II-4c to II-4b are documented in Table S1. The blocks had a length and thickness of about 10 and 20 cm respectively, encompassing generally sublevels Schöningen 13 II-4c, II-4bc and II-4b (Fig. S1). It has to be noted that the nomenclature of the 13 II-4 sublevels was not unified in the past and that layers 4bc, 4b(c) and 4b/c reflect the same unit.

Sampling for palynological, sedimentological and aquatic microfossil analyses. – Sixteen blocks have been sampled for palynological and geochemical analyses and 18 blocks for aquatic microfossil analyses at up to 0.5 cm resolution (Table S1).

The single sample named '*Betula* trunks', which was collected by Brigitte Urban during the excavation campaign in 1995 from sublevel 13 II-4c, lies outside of the excavated area. It was taken from a sediment layer that consisted of a number of completely decayed birch trunks only identifiable by the sediment-filled, fossilized tree rings.

Samples of the Zeugenblock 13 II (2018) (ZB 2018), a sediment reference column of sublevels 13 II-4c, 13 II-4ab and upper layers (5d1 and 5d2) (Fig. 3), were analysed within the context of an ongoing research project on newly excavated archaeological horizons including a new composite profile of the Reinsdorf sequence (Para-Reference Profile 13 II (2014) (PRP 2014)) (Altamura *et al.* 2023; Tucci *et al.* 2021; Urban *et al.* 2023) independently of the block samples. Relevant geochemical and palynological data from the ZB (2018)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1023
6930
7706
9934
15636
15632
15038
9863
10980
15058
15085
15070
15187
12283
Zeugenblock (ZB) 13 II (2018)
12927
11494
14972
12048
15558
14938/14939
15561
N
Betula trunks
10 5 0 10 20 30 m
Legend
Elevations (m a.s.l.)
High : 104.5
Low : 98.7
Sublevel
b
b/c
c
Betula trunks
Zeugenblock (ZB) 13 II (2018)
Investigated area
Blocks

Fig. 3. Map showing the positions of the high-resolution investigated blocks of Schöningen sublevels 13 II-4c (=c, c(b)), 13 II-4b/c (=b/c) and 13 II-4b (=b) of the 'Spear Horizon' within the site, collected in 1995, sample '*Betula* trunks', and of the Zeugenblock 13 II (2018) (Urban *et al.* 2023). The blue boxes represent artificial areas created for this paper to clarify the presentation of data. The palaeoshore has been reconstructed based on the elevations of the top of the calcareous muds of layer II-4c (modified after Böhner *et al.* 2015).

are adduced for comparison with the block profiles in this paper.

Methods

Lithological description, sedimentological and geochemical analyses. – The profiles were described using the field methods of Ad-hoc-Arbeitsgruppe Boden (2005) for assessing the texture, whereas the colour was determined according to the Munsell soil colour charts (Munsell Color 2010) (Table S1). Total organic carbon (TOC) and total nitrogen (TN) were determined using a CHNS/O elemental analyser (Perkin Elmer 2400 Series II CHNS/O), after the removal of carbonates with HCl. Organic matter (OM) was calculated from the TOC content (OM % = TOC × 1.72). Carbonate content was analysed by gasometric determination with the Scheibler apparatus and soluble salts were determined by electrical conductivity according to VDLUFA (1991). The pH was determined in a 1:5 suspension at 60 °C of dried soil and a 0.01 M $CaCl_2$ solution using a glass electrode. Elemental analysis was carried out at 60 °C in dried and ground samples using an X-ray fluorescence spectrometer (Bruker S2 PICOFOX). In order to eliminate potential matrix effects centred-log-ratios (clr) were calculated from the original net counts (cts) of Ca, Ti, K, Fe and S. Furthermore, log-ratios were calculated for Ca/Ti (Spofforth *et al.* 2008; Weltje & Tjallingii 2008; Weltje *et al.* 2015; Ramisch *et al.* 2018; Kasper *et al.* 2021). All analyses were carried out in the soil laboratory of the Institute of Ecology of Leuphana University, Lüneburg, Germany.

Pollen analyses. – For palynological sample preparation standard methods including carbonate removal by 10% HCl, dispersion with 10% KOH, flotation using sodium polytungstate hydrate ($3\ Na_2WO_4 \cdot 9\ WO_3 \cdot H_2O$) and acetolysis to dissolve cellulose were applied (Erdtman 1960; Faegri & Iversen 1989; Moore *et al.* 1991). Five tablets of *Lycopodium* spores were added to each sample at the beginning of the preparation to calculate the sporomorph concentration (Stockmarr 1971). Residues were embedded in glycerine. Slides (24 × 32 mm) were analysed under a transmitted light microscope for pollen and non-pollen palynomorphs at 400× magnification. The palynomorph identification atlases of Faegri and Iversen (1989), Moore *et al.* (1991) and Beug (2004) were used. The pollen sum, on which percentages of all taxa are based, is composed of terrestrial taxa of arboreal (AP) and non-arboreal pollen (NAP). Taxa from aquatic plants, Cyperaceae, Ericaceae and cryptogams were excluded from this sum. Pollen percentages and concentrations were computed and graphed using the software package TILIA (Grimm 1990). A combination of stratigraphically constrained cluster analysis (CONISS) (Grimm 1987) and conventional interpretation was applied to describe the pollen diagrams in detail.

Ostracod, diatom and charophyte analysis. – In total, 66 samples were analysed for ostracods and charophyte gyrogonites, and diatom analyses were performed on 58 samples of the sediment blocks underlying the archaeological remains of the 'Spear Horizon'. Ostracod and gyrogonite sample preparation involved overnight immersion of ~3 g of dry sediment in 4% H_2O_2 and subsequent washing through stacked mesh sieves (250, 125 and 63 μm) to separate the sample in different size fractions. If numbers were sufficient, 300 ostracod valves were separated from the 250 μm fraction using fine brushes. In samples containing fewer than 300 valves and for gyrogonites all specimens in the 250 μm fraction were picked. In the other two sieve fractions, valves and gyrogonites were counted to assess the respective concentrations. Valves were identified under a Leica M80 stereoscopic microscope using standard identification keys (e.g. Meisch 2000; Fuhrmann 2012).

For diatom analyses, 0.1–0.15 g of dry sediment was treated for each sample following the method of Kalbe & Werner (1974) with minor modifications. Permanent microscopic slides were prepared with Naphrax® as the mountant and counting as well as identification were performed using a light microscope (Leica DM 5000 B equipped with a ProgRes® CT5 camera) with differential interference contrast under oil immersion at 1000× magnification. Concentrations were determined by adding known quantities of polystyrene microspheres to the prepared sample (Battarbee & Kneen 1982) and, if possible, 400 valves per sample were identified using relevant literature and publications (e.g. Krammer & Lange-Bertalot 1986, 1988, 1991a, b; Lange-Bertalot *et al.* 2017). Analyses of samples lacking diatoms or with very low concentration were stopped when 500 microspheres and not more than 10 diatom valves had been counted. Aquatic microfossils were identified to the highest possible taxonomic resolution depending on the preservation of remains.

Samples containing less than 10 ostracod or diatom valves were omitted from percentage calculations and only numbers and concentration are displayed. Stratigraphic diagrams for the sediment blocks were created with C2 ver. 1.7.7 (Juggins 2007) and the pie charts were created using Excel® and subsequently edited in CorelDRAW® 2021.

Design of maps. – The digital elevation model is based on the top of sublevel 13 II-4c (Böhner *et al*. 2015). The topography of the investigated area and results of the geochemical, palynological and microfossil analyses of the block profiles (ID numbers) were created based on the reconstructed sublevel II-4c surface with reference to elevations of lithologically and palynologically defined boundaries within the particular profile (Fig. 3).

Results

Palaeotopography, lake and terrestrial environments

Palaeotopography. – The geographical locations of the block profiles within the archaeologically excavated area, sized 50 × 50 m, of the so-called Zeugenblock (2018) (Urban *et al*. 2023) and the single sample '*Betula* trunks' of sublevel II-4c (1995) as well as the palaeoecologically investigated block profiles, are indicated in Fig. 3. The micro-palaeorelief of the investigated lakeshore area shows that maximal differences in elevation of the highest and lowest points of transects 1-1 and 2-2, which are running parallel to the lakeshore (NW to SE) amount to 3 and 0.5 m, respectively. The SW to NE running 28-m-long transect 4-4 and cross-section 3-3, which is about 45–50 m long, show differences in elevation of about 2 and 3.5 m between the highest and lowest points of the block sample positions, respectively (Fig. 4).

Carbonates, TOC, TN, C/N and element ratios. – The lacustrine organic sediments of the investigated small block profiles can be classified as calcareous, Characeae-rich muds (sublevel II-4c) and organic, in some positions slightly calcareous, muds (sublevel II-4bc), (Succow & Joosten 2001). Sublevel II-4b is a carbonate-free organic mud. The two sublevels II-4bc and II-4b bear faunal remains (Table S1, Fig. S1). The geochemical results of all analysed blocks are presented with small diagrams on the site map in Fig. S2. Looking closer at the site-specific development of sublevels 13 II-4c, 13 II-4bc and 13 II-4b bearing the zoological remains, differences in lithological and geochemical characteristics are obvious. The Munsell colour connotation of sublevel 13 II-4c of the block profiles ranges between grey (10YR 6/1) and brown (10YR 5/1) (Table S1). This horizon contains up to 80% $CaCO_3$, is relatively poor in organic carbon (4.5% on average) and total nitrogen (0.4% on average) with C/N ratios of 11 on average. The Munsell colours of the

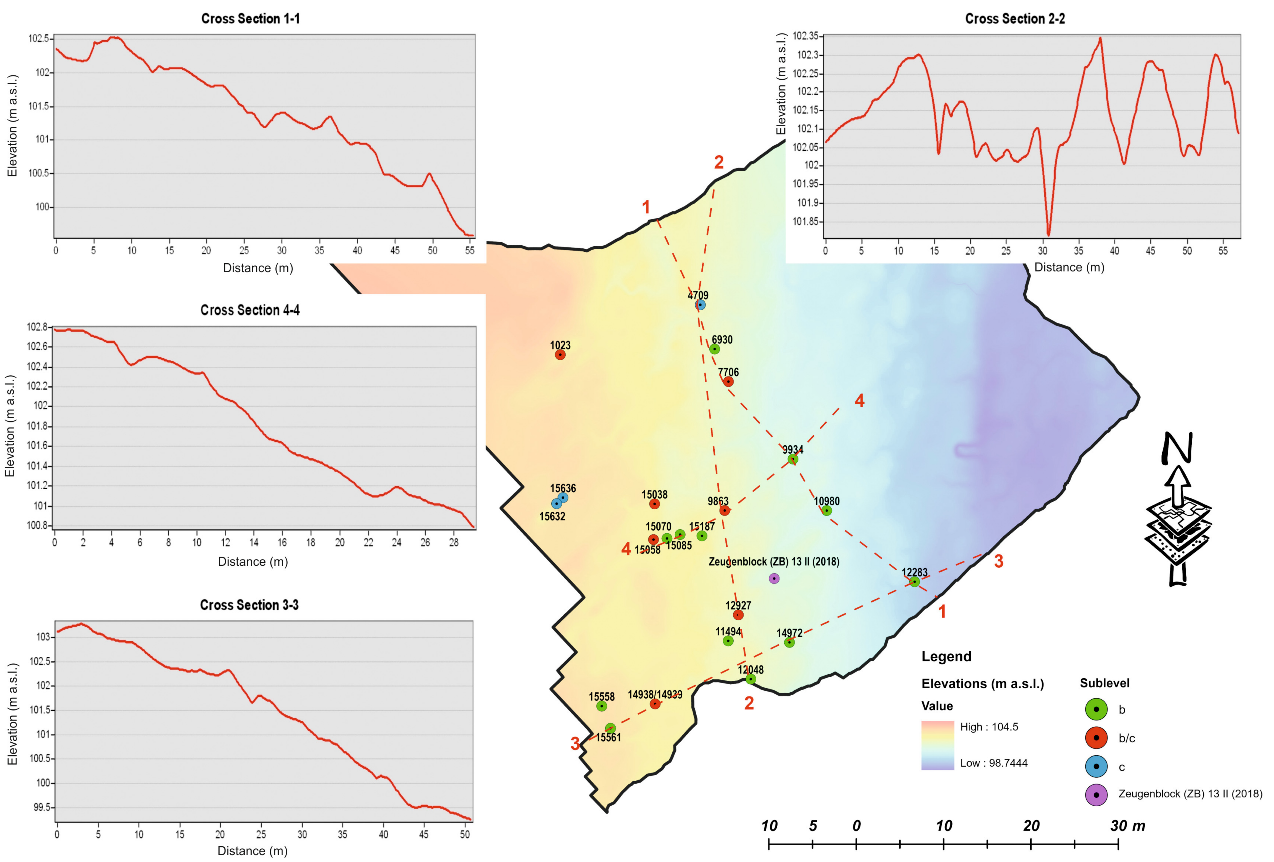

Fig. 4. Cross sections 1-1, 2-2, 3-3 and 4-4 running through the excavated find horizons 13 II-4c, II-4b/c and II-4b, respectively and the levelled position of the pollen sample directly underlying the zoological remains or artefacts. The palaeoshore has been reconstructed based on the elevations of the top of the calcareous muds of layer II-4c (modified after Böhner *et al*. 2015).

organic muds of sublevel 13 II-4b range between black, very dark brown (10YR 2/1, 10YR 2/2) and very dark grey (10YR 3/1). This horizon is mainly carbonate free and consists of 16% TOC and 0.8% TN on average, respectively, with a mean C/N ratio of about 20. Sublevel 13 II-4ab shows decreasing carbonate and increasing TOC and TN values, characteristic for a transitional depositional environment.

Three block profiles (ID 15558a, ID 15661 and ID 12927; Figs 3, 5) were analysed as examples for their total element content and compared with data of equivalent (sub)levels of the Zeugenblock (ZB) 13 II (2018), situated close to block 12927 (Fig. 2).

The transition from sublevel 13 II-4c into II-4b in all analysed block-samples is characterized by a distinct reduction in carbonate content visible in both the quantitative $CaCO_3$ and the Ca(clr) data. This transition is parallelized with the shift from sublevel 13 II-4c to II-4bc which has been described for the Zeugenblock (Fig. 5). The deposits show an increase in minerogenic material, for example Ti(clr), K(clr) and Fe(clr) towards the top of the blocks. Within block 12927, the TOC content shows a slight increase, i.e. higher organic contents are reached in sublevel II-4b, whereas block 15561 reveals decreasing TOC values and remaining block 15558a shows slightly dynamic TOC contents oscillating between 8% and 10% but with a general decreasing trend towards the top of the block. A similar development over this transition is observed in the TOC/TN ratio within the blocks.

Palynology. – Pollen spectra and pollen diagrams of the 16 blocks are presented in Figs S4–S13. The 12-cm-long percentage pollen diagram of block ID 4709 was examined in 1-cm intervals (Figs 2, 6, Table S1). The lower part (13.5–8 cm), which belongs to the calcareous mud of sublevel II-4c, is characterized by high amounts of aquatic and wetland plants (20–40%). Heliophile herbs like Apiaceae, *Artemisia*, Asteraceae, Cichoriaceae, Rosaceae and Poaceae dominate among the NAP, which amount to 30–40% in total. *Betula* and *Pinus* are the prevailing wooden taxa, and the pollen values both scatter at around 30–40%. Pollen of other wooden taxa like *Salix* spec., *Alnus* cf. *viridis*, *Myrica*, *Juniperus*, *Larix* and *Picea* is very rare. The transition into the upper organic-rich, calcareous mud/detritus assigned to unit II-4c and II-4c(b), respectively, is characterized by a significant increase in Cyperaceae, Poaceae and other heliophile taxa as well as a decrease in aquatic and wetland plants (8–6 cm). The NAP is increasing whereas *Betula* values slightly decrease (to around 20%) to the top, while numbers of *Pinus* remain as before, scattering around 30–40%. The uppermost sample at 1.5 cm, which was directly overlain by a fully preserved horse skull, is characterized by a strong decrease in Cyperaceae (Figs 6, 7, 10).

The pollen concentration diagram of block ID 4709 clarifies that the total amount of pollen lies between 1×10^5 and 2×10^5 grains g^{-1} sediment except for at depth 5.5 cm where it reaches 2×10^6 total grains g^{-1} (Fig. S3 left, right).

The percentage pollen diagrams of all analysed blocks (Figs S5–S13) give detailed site-specific information, which will be described here by selected examples. Pollen profile ID 15561 of layers II-4c and 4b, and the adjacent profile of location ID 15558a of II-4b, both 7.5 cm long (Figs 2, 3, S5, S6), show persisting dominances of *Betula* in both sublevels and apart from this a similar composition and comparable amounts of NAP as found in ID 4709 (Fig. 6). The two pollen spectra of ID 15038 of

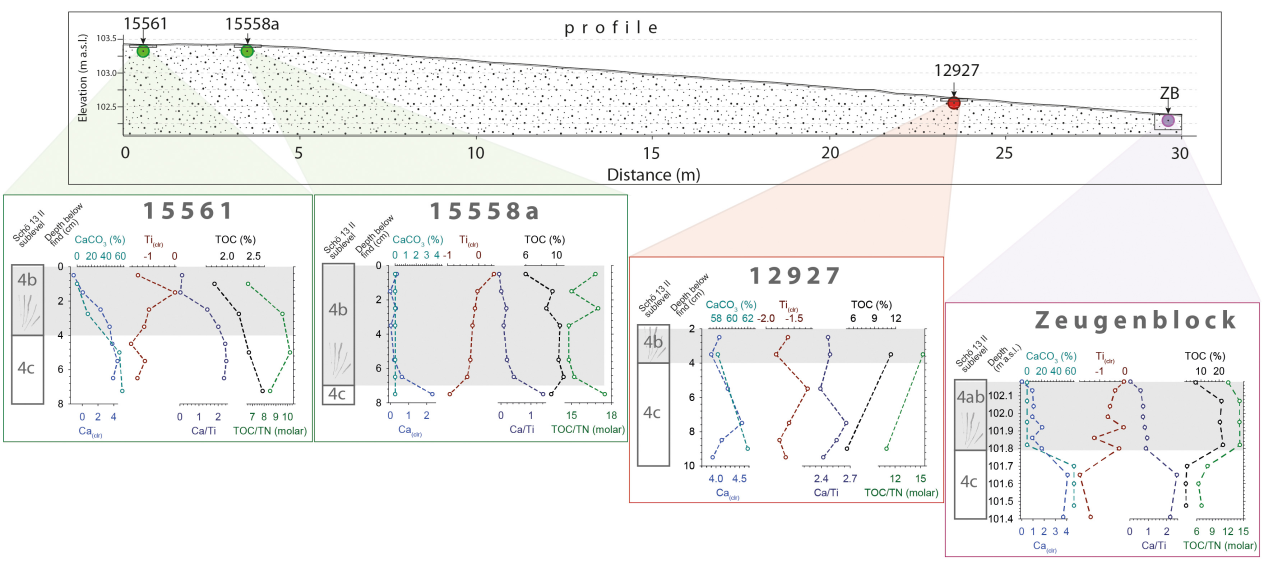

Fig. 5. Comparison of geochemical parameters of sublevels 13 II-4c and II-4b of block samples ID 12927, ID 15 661 and ID 15558a (II-4b = II-4ab) with equivalent Zeugenblock (ZB) 13 II (2018) layers (Urban *et al.* 2023).

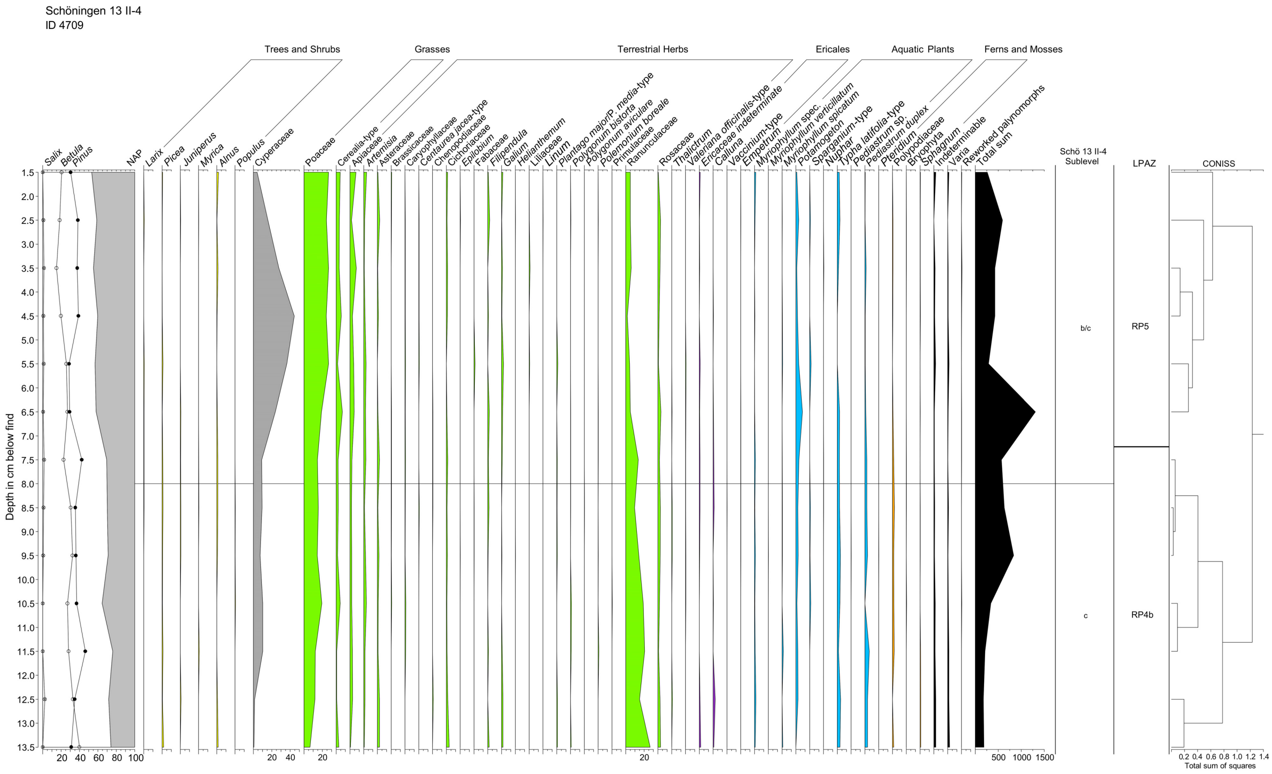

Fig. 6. High-resolution percentage pollen diagram of block ID 4709.

II-4b/c (Fig. S13 bottom) show values of about 35% of *Betula* and *Pinus* in the bottom sample at 2.25 cm whereas *Pinus* increases (up to 60%) and *Betula* decreases to 20% in the topmost sample (0.5 cm), which was collected directly below the pelvis of a horse. The same features can be observed for blocks ID 12927 and ID 15558b (Figs S8 and S12 top). The pollen spectrum of the so-called '*Betula* trunk' sample from sublevel II-4c is dominated by *Betula*, wetland and aquatic plants (Figs 7, S4).

The spatially and chronologically (from layer II-4c to 4b/a) arranged pie chart diagrams give an insight into the dominances of pollen groups and taxa of the time immediately before or in the course of the deposition of the particular faunal remains in the 'Spear Horizon' (Fig. 7). Among the wooden taxa *Pinus* is often dominating over *Betula* in the II-4b sublevel samples, whereas *Betula* and *Pinus* occur with about equal amounts in most of the II-4b/c layers. *Betula* is the dominant component in the southern and western part of the excavated area (ID 12927, 4b/c; ID 14938, 4b/c; ID 15561, 4b; ID 15558b, 4b; Fig. 3). Cyperaceae and Poaceae are present with high proportions in most of the diagrams.

As the digital elevation model used in this paper is based on the top of layer 4c (Böhner *et al*. 2015), it is plausible that the youngest samples/sites with ID 9934, ID 10980, ID 12283, ID 14972, ID 12048 and ID 6930 from sublevel II-4b reveal lower numbers of aquatic and wetland plants than for example the 'Birch trunk' sample of sublevel II-4c or samples from sublevel II-4bc, situated at a lower elevated position (Fig. 4).

Aquatic microfossils. – The concentration and composition of aquatic microfossil remains vary significantly throughout and among the individual sediment block profiles of the 'Spear Horizon' (Fig. 8). In particular, sublevel II-4b is characterized by low microfossil concentrations and samples void of remains, whereas sublevel II-4c generally contains higher numbers of ostracods. The ostracod assemblages are mainly dominated by juvenile Candonidae together with *Limnocythere inopinata*, *Cyclocypris* taxa, *Ilyocypris bradyi* and *Prionocypris zenkeri* (abundances on average 55, 15, 11, 8 and 4%, respectively). The diatom assemblages are overall composed of tychoplanktic taxa (on average 73%) with small fragilariod species clearly dominating the assemblages (mainly *Pseudostaurosira brevistriata*, *Pseudostaurosira elliptica*, *Staurosira venter* s.l., *Nanofrustulum sopotensis* and *Punctastriata lancettula*; Figs S14 and S15). Benthic species were found in low abundances, for example *Epithemia adnata* (2%) and *Rhoicosphenia abbreviata* (1%). Planktic taxa such as *Stephanodiscus* spp. are rare. The block corresponding to ID15636 represents a calcareous mud profile (sublevel II-4c) with high ostracod (on average 1313 valves g^{-1} dry weight, DW) and comparibly elevated charophyte gyrogonite (on average five specimen g^{-1} DW)

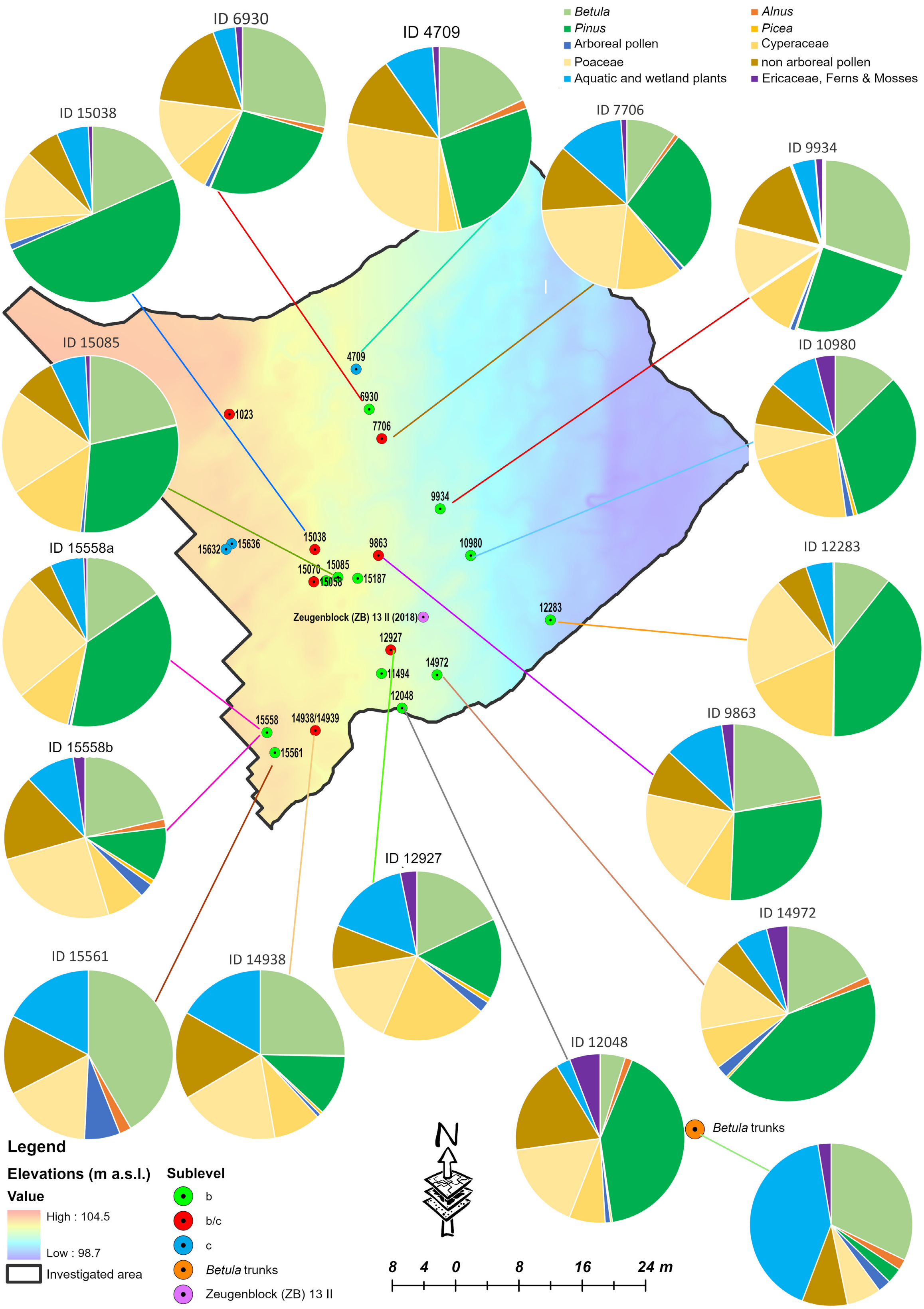

Fig. 7. Pollen pie charts of the sediment sample underlying, respectively bearing the particular faunal remains (see Table S1) and a sample of tree-rings from a mineralized *Betula* trunk layer within sublevel 13 II-4c, collected by Brigitte Urban in 1995. The palaeoshore has been reconstructed based on the measured elevations of the top of the calcareous muds of 13 II-4c (modified after Böhner *et al.* 2015).

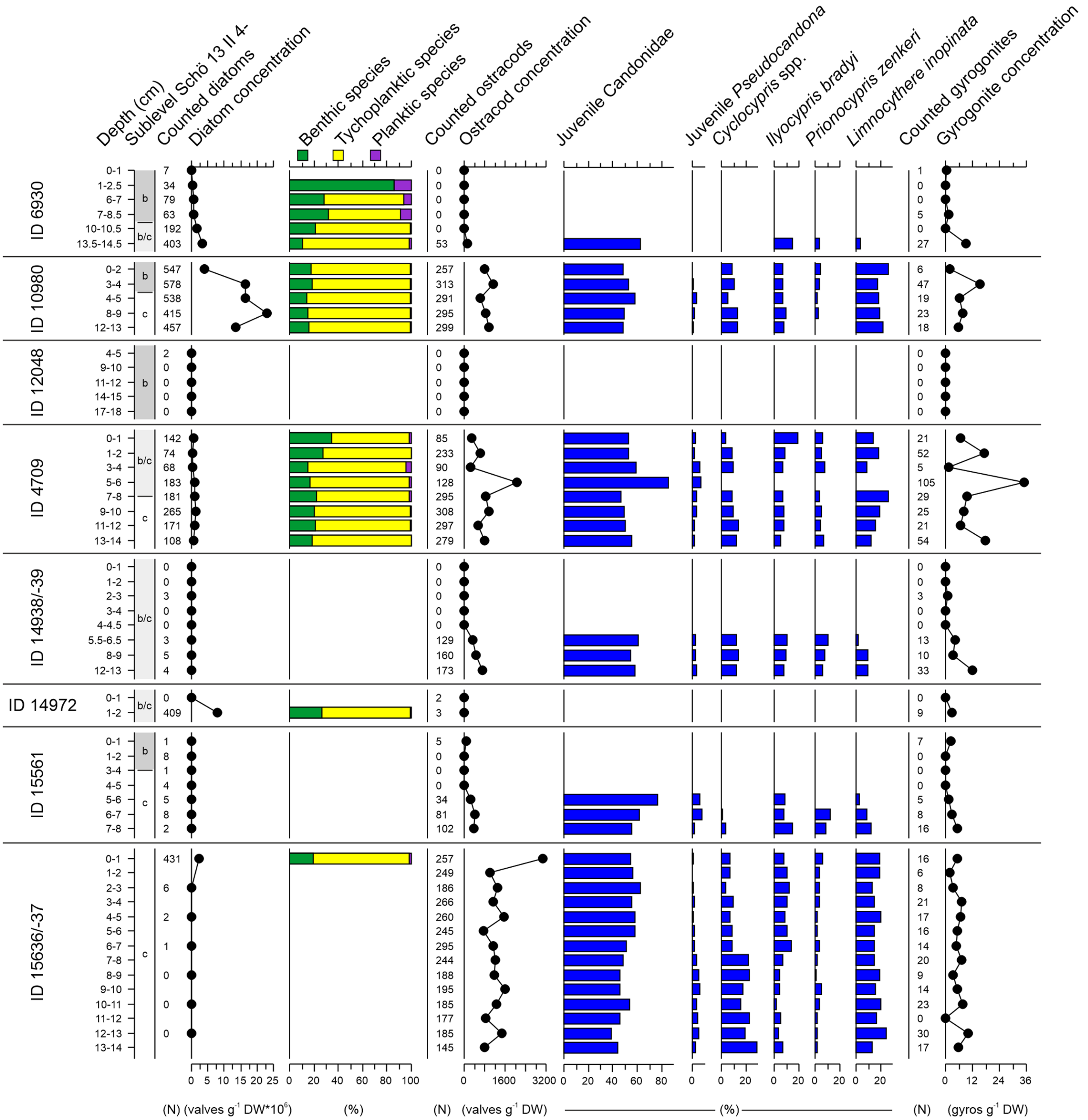

Fig. 8. Aquatic microfossil numbers, concentrations, proportions of different diatom lifestyles and most abundant ostracod taxa of eight selected sediment blocks with corresponding artefact IDs covering sublevels Schöningen 13 II-4c, 13 II-4b/c and 13 II-4b of the 'Spear Horizon'.

concentrations. Ostracod taxa show a shift from high abundances of *Cyclocypris* spp. (up to 29%) in the lower half to high abundances of *I. bradyi* (up to 15%) in the upper half of the profile. Diatoms were only present in the uppermost sample. The ID 4709 block depicts the transition from sublevel II-4b to 4b/c and is marked by overall decreasing microfossil concentrations as well as slightly increasing proportions of benthic diatom taxa towards the top (35%). A short excursion, characterized by a prominent increase in ostracod and gyrogonite concentrations and the temporary disappearence of several ostracod taxa, is visible at 5–6 cm depth. The profile ID 6930 shows generally decreasing microfossil concentration from sublevel II-4c/b to b for all groups. Ostracods and gyrogonites were mainly found in the lowermost sample (13.5–14.5 cm) and in low concentrations (ostracods, 127 valves g^{-1} DW; gyrogonites, 9 gyros g^{-1} DW). Diatoms show a significant reduction in tychoplanktic species (88% in lowermost sample) in favour of especially benthic taxa (up to 86%) towards the top.

Investigation of sediment samples directly underlying the archaeological artefacts reveals high numbers of samples void of diatoms and ostracods (Fig. 9). In particular, sublevel II-4b often lacks microfossil remains. The blocks ID 15187 and ID 11494, which contain mainly benthic diatoms but no ostracods, as well as ID 10980, represent exceptions and show increased proportions of tychoplanktic diatoms together with a diverse ostracod fauna. Tychoplanktic diatom taxa mainly dominate sublevels II-4b/c and II-4c, if present. Ostracods can be found in sublevel II-4c with varying proportions of the individual taxa, but juvenile Candonidae and *L. inopinata* generally show the highest abundances. Block ID 9863 is the only example where ostracods are present in sublevel II-4b/c. The assemblage is composed of juvenile Candonidae, *I. bradyi* and *P. zenkeri*.

Archaeology

Distribution of the blocks and archaeological evidence. – Almost two-thirds of the entire archaeological assemblage are distributed along a longitudinal band running across the site in the north–south axis. Within this 60-m-long, 10-m-wide band, circular clusters of archaeological remains can be defined, where more than 100 remains per square metre accumulate, with the densest concentrations located in the northern half of the band (Fig. 2). This probably corresponds to the area where human activity was more intense. Three blocks (ID 4709, ID 6930 and ID 7706) were collected from this area of intense activity and are associated with some of the main clusters. Another five blocks (ID 9863, ID 15187, ID 12927, ID 11494 and ID 12048) were recovered from the southern half on the band, where the density of finds is lower than in the northern half, but still higher than in other areas of the site (Fig. 2). This band was interpreted as the main shoreline of the Schöningen palaeolake during the formation of the 'Spear Horizon' (Böhner *et al*. 2015; Turner *et al*. 2018).

To the east of the main band, downslope to the lake's basin, a second area of human activity can be defined (Figs 3 and 4). This area, separated from the main band by a step and a narrow strip with fewer finds, is characterized by a lower density of remains, compared with the main band (Fig. 2; García-Moreno *et al*. 2021). Here, around one-third of the assemblage distributes across 1800 m^2 (almost 50% of the excavated surface). In this area finds appear to be more scattered than in the main band. However, the similar preservation of faunal remains (including the presence of black staining at the surface of the bones) and the appearance of several skeletal portions in anatomical connection indicate that this area formed under similar shallow water conditions to the main band (Turner *et al*. 2018), probably as a result of changing water table levels and a shift in the position of the lake's shoreline (García-Moreno *et al*. 2021). Blocks ID 9934, ID 10980, ID 12283 and ID 14972 come from this area, more specifically from its southern part, where the transition between both areas is more diffuse (Fig. 2). A third area can be defined upslope to the west of the main band, based on the density and the degree of preservation of the archaeological assemblage. In this area, only a few finds were recovered. Finds appeared dispersed over a vast expanse, with some of them concentrating in small clusters. Faunal remains from this area were highly weathered and lack the black organic staining characterizing bones from the other areas, which indicates that they were exposed for a certain time (Turner *et al*. 2018). Consequently, this area is considered to have been dryland during the formation of the 'Spear Horizon' (Böhner *et al*. 2015; García-Moreno *et al*. 2021). Up to 11 blocks originate from this area: ID 15038, ID 15070, ID 15085 and ID 15058 were located next to the main band, whereas blocks ID 14938, ID 15558 and ID 15561 come from the southernmost part, where very few finds were recovered. Finally, blocks ID 1022/ID 1023 and ID 15632/ID 15636 come from the northern and middle parts of this area respectively, and they are associated with some small clusters.

Faunal remains. – A majority of bones recovered from atop the processed sediment blocks are from horse (*Equus mosbachensis*, Table S2, Fig. 10). Likewise, horse bones are abundant in the overall 'Spear Horizon' assemblage, probably accounting for more than 90% of the nearly 15 000 faunal remains (Voormolen 2008; van Kolfschoten 2014; van Kolfschoten *et al*. 2015a; Hutson *et al*. 2020; García-Moreno *et al*. 2021). Several blocks preserved red deer (*Cervus elaphus*), aurochs (*Bos primigenius*), and bison (*Bison priscus*) remains, and a single block contained a bone from an elephant (*Elephas antiquus*). These species are proportionally more abundant in the sediment blocks than in the 'Spear Horizon' faunal assemblage; in particular, elephant is exceedingly rare in the overall bone accumulation. All of the bones are very well preserved and often intact, including complete skulls with articulated cranium and mandibles (Fig. 10A, B). Bone surfaces are largely intact and preserve several phases of taphonomic modifications. Cut marks show a clear association with hominin hunting and butchery activities along the lakeshore (Table S2). A horse pelvis (ID 7706) with cut marks also shows carnivore tooth pits. Evidence from the overall assemblage suggests that carnivores probably scavenged from hominin kills near the Schöningen lakeshore (Hutson *et al*. 2021). Several bones preserve dark surface staining, which probably occurred when the bones came into contact with decaying plant material in the shallow waters near the lakeshore and were quickly buried.

Discussion

The two lacustrine sedimentary units of layer II-4c and II-4b/c, respectively II-4b/4a reflect a continuous lake

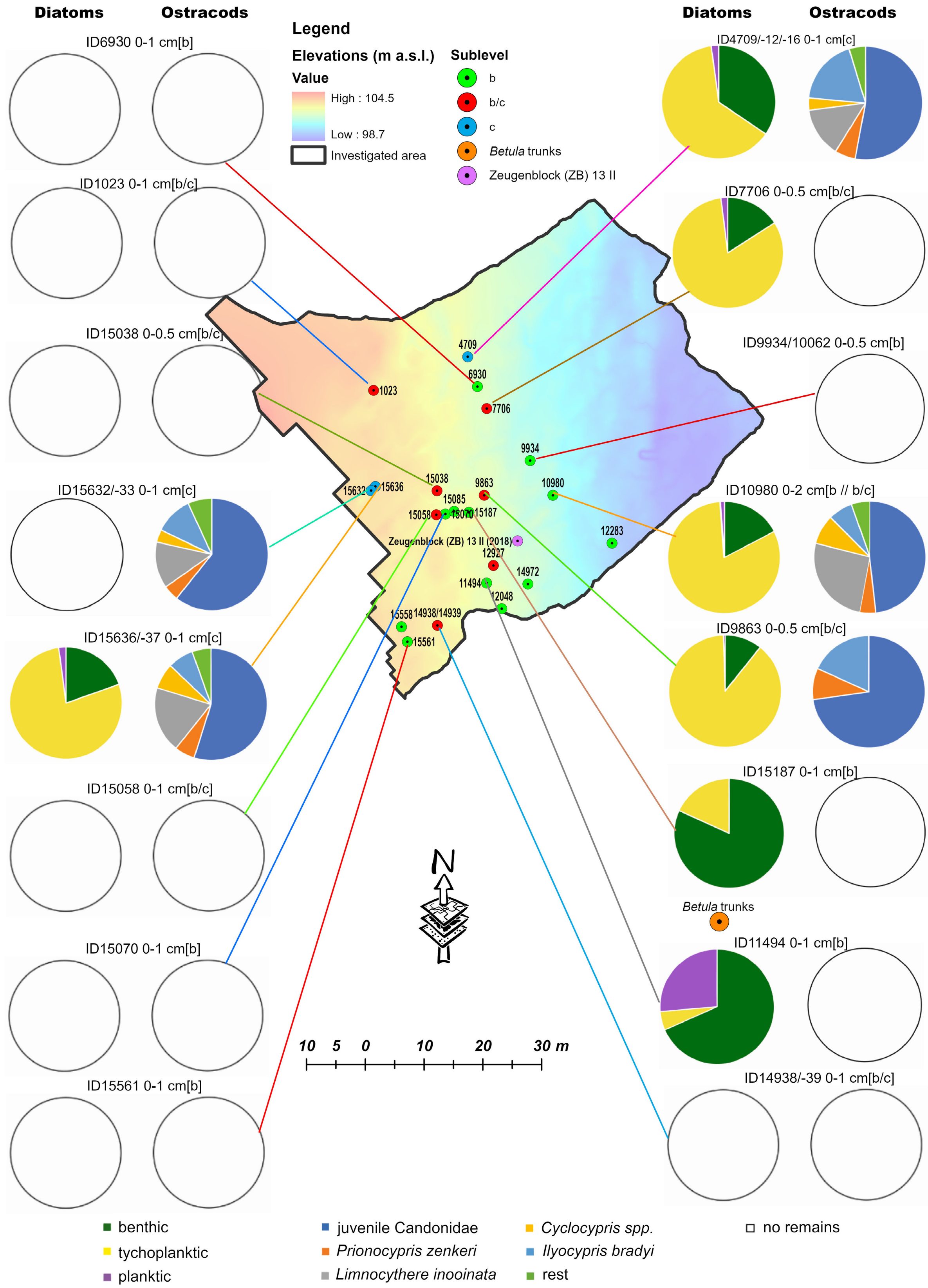

Fig. 9. Diatom and ostracod pie charts of the sediment samples underlying, respectively bearing the particular faunal remains (see Table S1). The palaeoshore has been reconstructed based on the measured elevations of the top of the calcareous muds of layer II-4c (modified after Böhner *et al.* 2015).

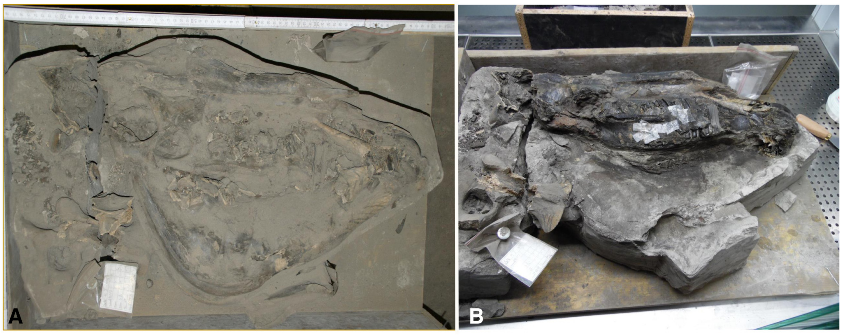

Fig. 10. A. Intact skull of horse (*Equus mosbachensis*) lying on top of block ID 4709. B. The same block after removal of the mandible.

level drop, which is represented by calcareous mud (II-4c), transitional calcareous, organic mud (II-4c(b)) and the youngest carbonate-free organic mud/detritus (II-4b, II-4a) of the silting-up sequence.

The transition between the two sedimentary units is interpreted with regard to its relative topographic position, with blocks ID 15561 and 15558a and 15558b located at the same and highest elevation, the Zeugenblock at the lowest elevation and block ID 12927 at an intermediate altitude in between (Fig. 5). In comparison with the Zeugenblock with the transition from sublevel 13 II-4c into II-4ab, the parameters analysed in block ID 12927 reveal a very similar pattern characterized by a reduction in carbonates and an increase in TOC and in C/N, suggesting a reduction in water depth (Wu *et al.* 2016). In particular, the rise in TOC/TN suggests a shift from aquatic to more submerged littoral or terrestrial vegetation (Meyers & Lallier-Verges 1999; Meyers 2003). These interpretations in combination with the increase in minerogenic material (Ti, K, Fe) point to a siltation of the palaeolake owing to increased minerogenic input from the catchment (Haberzettl *et al.* 2008; Kylander *et al.* 2011; Kasper *et al.* 2015, 2021), arguing against a lake level drop caused by reduction of moisture availability. The proxies in block ID 15558a, which is located on a topographically higher position, show similar, although weaker trends. The very low carbonate contents on the base of the block and an overall higher TOC content within the entire section indicate the deposition of the sediment within a littoral environment close to the shore of the paleolake. The elevated, but variable, TOC/TN between 15 and 17 further suggests a mix of littoral and shore/terrestrial vegetation (Meyers & Lallier-Verges 1999). The carbonate and minerogenic proxies in the transition between II-4c and 4b within block ID 15561 show a trend similar to those for the ZB and block ID 15558a, suggesting a siltation of a shallow water body. However, decreasing TOC contents and TOC/TN values on a general low level might also point to a rather quick desiccation and thus a quick carbon mineralization. This is additionally supported by the lowest TN values of all analysed blocks, indicative of a comparable fast turnover time (Janssen 1996; Maerki *et al.* 2009; Gudasz *et al.* 2015). The blocks at the highest and lowest positions are vertically offset only about 1 m, while the lateral offset is ~30 m (Fig. 5). Hence, the small but notable differences in the geochemical and sedimentological data across the transect might well reflect not only the stage of siltation of the shallow palaeolake, but uniquely depict the sequence of the siltation process over time. Additionally, the increase in Fe at a certain depth in the profiles (similar to Ti in Fig. 5), might further reflect soil formation processes within exposed lacustrine deposits after the process of siltation of the lake had ended (Schülli-Maurer *et al.* 2007; Malkiewicz *et al.* 2016).

The eight exemplary sediment blocks, along with the faunal remains underlying samples examined for aquatic microfossil remains, display a highly diverse depositional environment across the 'Spear Horizon' (Figs 8, 9). Although positioned at close distance (~5 m apart, Fig. 3) and of comparable thickness, blocks ID 4709 and ID 6930 show very different microfossil assemblages related to the different depositional environments of layers II-4c, II-4b/c and II-4b.

Continuously high ostracod concentrations along with highest charophyte gyrogonite concentrations are indicative of submerged conditions throughout deposition of profile ID 4709. This suggests a water depth of around 0.5–2 m for sublevel 13 II-4c of the Reference Profile based on its charophyte assemblage (Krahn *et al.* 2021). Furthermore, the authors proposed that a period of cooler climates with reduced vegetation cover led to increased surface stream inflow fed by small springs from the nearby mountain range Elm. Mesorheophilic ostracods (e.g. *P. zenkeri*), together with high proportions of small tychoplanktic diatoms (e.g. *P. elliptica*, *S. venter* s.l.), as found in block ID 4709 and several other samples representing the calcareous mud of layer II-4c (Figs 9, S14, S15), also suggest flowing waters with some level of disturbance. High abundances of tychoplanktic diatoms such as the small fragilarioid species occurring at Schöningen site 13 II (Krahn *et al.* 2021) were related to erosion (Hickman & Reasoner 1994, 1998), environmental instability (Denys 1990) and longer periods of ice-cover on the lake (Lotter & Bigler 2000). Increased fluvial activity is detected close to the position of ID 9863 by the highest proportions of small tychoplanktic diatoms of all samples and markedly increased abundances of *I. bradyi* and *P. zenkeri*, ostracod species which prefer flowing waters or even avoid standing waters (Meisch 2000). Interestingly, profile ID 15636 shows an increase in *I. bradyi* and *P. zenkeri* towards the top, which could indicate increased turbulence towards the end of deposition of sublevel II-4c before the transition into sublevel II-4b/c.

Rapidly decreasing remain numbers in all aquatic microfossils groups of profile ID 6930, which is mainly composed of organic mud (sublevel II-4b), support decreasing lake levels and successive sillting up. We propose that the high proportion of benthic diatoms in favour of decreasing tychoplanktic taxa at the top of layer II-4b in profile ID 6930 and the artefact underlying sample ID 11494 are related to calmer conditions at the lakeshore connected to the silting up of the site and/or shorter periods of lake-ice cover during the transition to moister conditions with a more densely vegetated catchment (Urban & Bigga 2015). Mainly barren samples for sublevel II-4b (Figs 8, 9) further document overall unfavourable conditions for the development of aquatic life or for preservation of both calcareous and silicious remains. This could indicate only temporary water coverage of the site during deposition of the archaeological assemblages.

The enrichment of pollen at the 5.5 cm depth of block ID 4709 might reflect an early stage of the onset of terrestrialization after a period of high lake level, when the layer was exposed at the surface for a longer period. Total pollen concentration or taxa specific amounts of this profile can neither be related to sediment type nor to particular vegetation changes deduced from the percentage pollen diagram (Figs 6, S11). This evidences that taphonomical influences during pollen deposition can widely be excluded. The change in the depositional nature of the lacustrine sediments coincides palynologically with an increase in grasses (Poaceae) and particularly of sedges (Cyperaceae), pointing to a general trend in terrestrialization from units II-4c(b) to II-4b, respectively II-4a (earlier terminology, Böhner *et al*. 2005). The '*Betula* trunk' sample of unit II-4c reflects for example a mainly aquatic and wetland flora with sparse riverine birch stands. A general decrease in *Betula*, which dominated local swamps during the formation of II-4c, is typical for the local pollen assemblage zone (LPAZ) RP4b and an increase in *Pinus* and in *Picea* in 4c(b)/4b characteristic for LPAZ RP5. These trends are demonstrated in the detailed pollen diagram of the Zeugenblock (2018) (Figs 1B, 3, 11). These observations are significant for a stratigraphical classification of the archaeological finds, which are mainly located in layers 4c(b) and 4b, respectively. These phases were characterized by a tessellated type of vegetation with very few *Picea* stands, which most

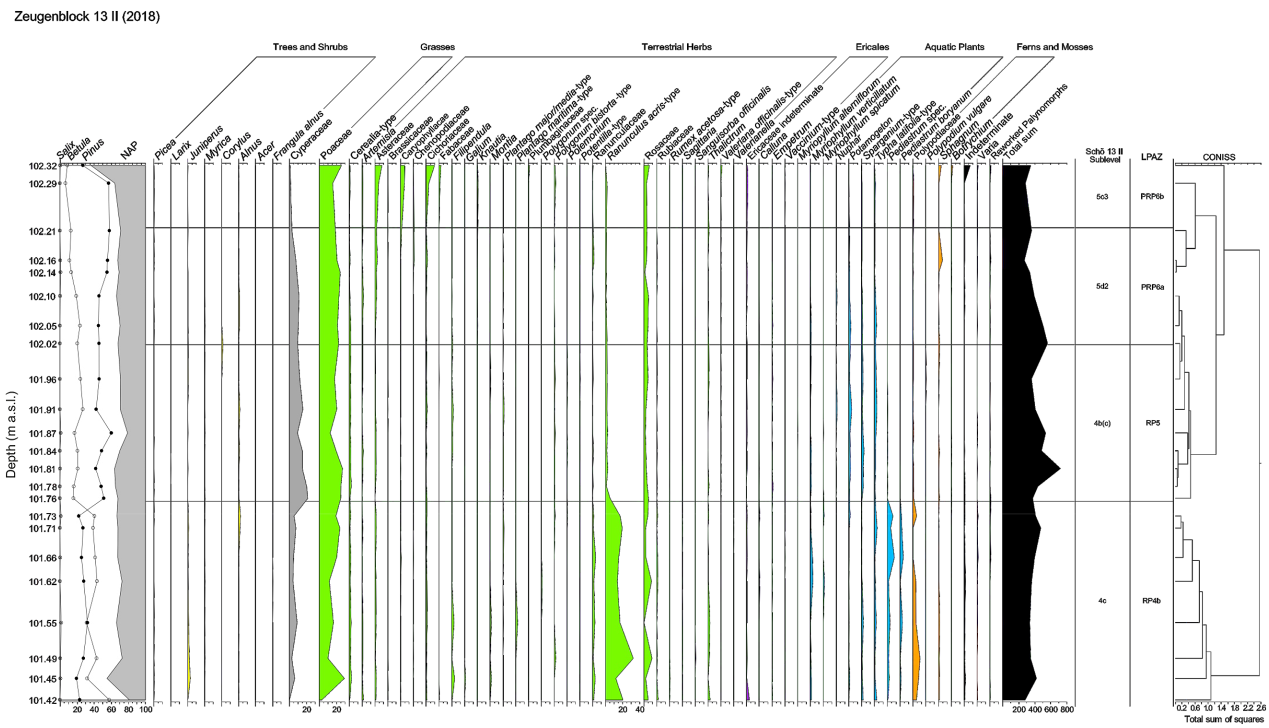

Fig. 11. Pollen diagram of the Zeugenblock (2018), modified from Urban *et al*. (2023). Of particular interest are sublevels II-4c and II-4ab (synonymous with 4b).

probably existed further away from the lake, *Larix*, which has occurred on the Elm mountain range and *Alnus* cf. *viridis*, *Salix* and *Betula*, which may have grown along watercourses. The reed and swamp vegetation was quite rich in *Carex* species, *Schoenoplectus*, *Typha* and *Ranunculus sceleratus*, and in submerged or floating plants like *Myriophyllum spicatum*, *Potamogeto*n species, respectively, and the salt tolerant *Zannichelia palustris*, recorded from plant macro and pollen records (Jechorek 2000; Bigga *et al*. 2015; Tucci *et al*. 2021). Among the grass-rich vegetation of the dryer, higher elevated stands (Fig. 4), a rich heliophile flora was distributed at the lakeshore.

The block samples directly underlying the faunal remains were collected from the transitional sublevel II-4c(b) and from the carbonate-free sublevel II-4b, whereby the oldest samples or those characteristic for layer II-4c are generally dominated by aquatic plants and *Betula*, illustrating high lake level (Figs 7, 11, Table 1). Among the wooden taxa, *Pinus* generally dominates spectra of the organic mud layer II-4b and II-4ab/4a, respectively, whereas grasses and Cyperaceae are predominant among the NAP, the latter underlining the onset of terrestrialization and lake level drop. As shown by taxa like *Chenopodium album*, *Chenopodium polyspermum*, *Urtica* sp. and *Rumex crispu*s (Jechorek 2000; Urban & Bigga 2015), animals as well as humans would have disturbed the area, leading to the distribution of a heterogeneous local flora (Fig. 7). In consequence of the small-scale surface inhomogeneities and the rather uneven local micro-topography parallel to the lake shore, an almost concurrent development of the deposits of layers II-4c(b) and II-4b along the shore is most likely. While sublevel II-4c is assigned to a cooler, very dry and grass-rich steppe (open woodland) phase, the landscape had returned to a grass-rich, moister, open woodland phase during deposition of II-4c(b)/4b (Table 1). The large mammals identified from the 'Spear Horizon' excavation, in addition to several carnivore species, small mammals, birds and fishes, also indicate a mosaic temperate environment with open

Table 1. Synthesis of palaeoenvironmental findings of archaeological horizon 13 II-4 ('Spear Horizon'). Biostratigraphic subdivision and vegetational phases relate to Urban *et al.* (2023).

Reinsdorf Sequence "Spear Horizon"					
Schöningen level 13	ID/Profile/ block	Depositional environment (geochemistry, aquatic microfossils, local and zonal vegetation)	Fauna Block taxa	Vegetation phases	Biostratigraphy
II-5c3	15558b	Strong increase of heliophytes (Artemisia, Poaceae a.o.), decrease of arboreal vegetation at the top of the sub-sublevel	*Bison*/*Bos* indeterminate, Bison/ Aurochs	Post-interglacial early steppe-tundra phase	Reinsdorf E
II-4b	9934, 15558a 12283, 15085 10980, 6930 12048, 15561 15187, 11494 15070	Decrease in $CaCO_3$ content; increase in minerog. elements; shift to lower C/N ratio ➔ decomposition ➔ quick siltation of the lake ➔ temporarily exposed surface with indication of soil formation processes at some locations Decreased numbers of aquatic microfossils ➔ unfavourable preservation conditions and/or temporary water coverage at sampling site Strong increase of grasses (Poaceae) and sedges (Cyperaceae) indicating terrestrialisation; tessellated type of local vegetation, *Alnus cf. viridis, Salix*, *Betula*	*Equus mosbachensis*, Mosbach horse *Cervus elaphus*, Red deer *Bos primigenius*, Aurochs *Bison*/*Bos* indeterminate, Bison/Aurochs *Palaeoloxodon antiquus*, Straight-tusked elephant	Second post-interglacial woodland phase	Reinsdorf D
II-4c(b)	9863, 15038 7706, 12927 4709, 14972 14938/14939 1023, 15058	Decrease in carbonate content; variable minerogenic elements (Ti, Fe, K); increase in (terrestrial) organic biomass ➔ quick siltation of the lake ➔ temporarily exposed surface with indication of soil formation processes Gradual transition from aquatic to more submerged littoral and/or terrestrial vegetation, expansion of *Pinus*, slight increase of *Picea*	*Equus mosbachensis*, Mosbach horse *Cervus elaphus*, Red deer *Bos primigenius*, Aurochs		Reinsdorf C
II-4c	15632, 15636 „*Betula* Trunks"	High carbonate content, high lake-level; mesorheophilic ostracod species and high abundances of small fragilarioid diatom species ➔ flowing waters and turbulence, possibly prolonged ice-cover Local *Betula* swamp forests, diverse aquatic vascular flora	*Cervus elaphus*, Red deer	Second post-interglacial steppe (open-woodland) phase	

grassland and woodland in proximity to the Schöningen lakeshore.

Human activity occurred along the former shoreline at the very beginning of a lake level drop and before intensive terrestrialization of the stands. It seems to have concentrated in open areas (northern part of the main band including area 1 (blocks ID 7706, ID 6030 and ID 4709) and stretching to the northern edge of the site, Fig. 2), whereas it thins out in slightly higher elevated areas that were covered by relatively closed birch swamp forests.

Conclusions

The archaeological layers of horizon Schöningen II-4 of the Middle Pleistocene Reinsdorf sequence developed during a relatively short period of gradually lowering lake level and terrestrialization along the shore of the palaeolake. This is concluded from the continuous and undisturbed sedimentological transition of the calcareous mud layer II-4c into the organic muds of layers II-4c (b) and II-4b, which is exceptional compared to older similar sedimentological transitions within the sequence that are generally accompanied by an erosional event. In relation to other similar sediment units of older parts of the Reinsdorf sequence with corresponding environmental information, the thin organic layers that embedded the archaeological finds could point to a rather short period of sedimentation and thus a quick siltation of the palaeolake. Aquatic microfossil assemblages indicate slowly flowing waters during deposition of sublevel II-4c, whereas a lake level lowering accompanied by more stable lakeshore conditions is depicted for sublevel II-4b, thereby supporting geochemical results. Decreasing abundances of small fragilarioid diatoms could also point to shorter periods of ice-cover on the lake and agree with the palynologically inferred development from cooler and drier towards moister conditions. The archaeological findings and faunal remains were concentrating at the bottom of the organic mud layers at the onset of a cool, continental phase at the end of the interglacial–glacial Reinsdorf sequence. Owing to their special topographical and spatial location, we conclude that layers II-4c(b) and II-4b, containing the archaeological horizons, developed rather synchronously.

Megaherbivores such as bison, elephant and aurochs and ungulates such as horse and red deer, predominantly found at the 'Spear Horizon' kill site, are indicative of an open, grass-rich type of landscape. During the presence of hominin groups at the palaeolakeshore of Schöningen II-4 a dry, grass-rich steppe, open woodland zonal type of vegetation with scattered occurrences of *Pinus*, far distant stands of *Picea* and a diverse local aquatic and riparian flora and fauna existed in NE Lower Saxony.

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Author contributions. – BU conceptualized and wrote most parts of the article; BU, KJK, ET, AGM, JMH, AV, MT and TK generated the data; BU, DF, TK, KJK, AGM, JMH and AV processed and visualized the data. BU, KJK, TK, AGM, JMH and AV wrote and all co-authors reviewed and edited the article. Project administration and funding acquisition were done by BU and AS, SGW and ET.

Data availability statement. – All data generated or analysed in this study are included in this published article and its Supporting Information files.

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Supporting Information

Additional Supporting Information to this article is available at http://www.boreas.dk.

Fig. S1. Exemplary images of the block sediments underlying the faunal remains (calcareous mud, light colours of sublevels 13 II-4c and II-4bc; organic mud, dark brown and reddish-brown colours of sublevels II-4bc and II-4b).

Fig. S2. Total organic carbon (TOC), total nitrogen (TN), C/N ratio and calcium carbonate content of selected block profiles related to the geographical position.

Fig. S3. Left, pollen concentration diagram of block ID 4709; right, pollen concentration diagram of block ID 4709.

Fig. S4. Pollen spectrum of the '*Betula* trunk' sample collected from tree-rings, filled with sediments of sublevel II-4c based on NAP calculation excluding (upper diagram) and including (bottom diagram) *Ranunculus acris*-type and Caltha-type.

Fig. S5. Pollen diagram of block ID 15561.

Fig. S6. Pollen diagram of block ID 15558a.

Fig. S7. Pollen diagram of block ID 12927.

Fig. S8. Pollen diagram of block ID 6930 (top) and block ID 12048 (bottom).

Fig. S9. Pollen diagram of block ID 12283 (top) and pollen spectra of block ID 15085 (bottom).

Fig. S10. Pollen spectra of block ID 9863 (top) and pollen diagram of block ID 9934 (bottom).

Fig. S11. Pollen diagram of block ID 15558b (top) and pollen spectra of block ID 14938 (bottom).

Fig. S12. Pollen spectra of block ID 10980 (top) and block ID 14972 (bottom).

Fig. S13. Pollen spectra of block ID 15038 (top) and block ID 7706 (bottom).

Fig. S14. Diatom assemblage of block ID 10980 with diatom numbers, diatom concentration (V, valves; DW, dry weight) and relative abundances of taxa >1%.

Fig. S15. Diatom assemblage of block ID 4709 with diatom numbers, diatom concentration (V = valves, DW = dry weight) and relative abundances of taxa >1%.

Table S1. Block ID numbers, sublevel Schöningen 13 II-4, area, average depth of strata/sublevel in centimetres, elevation metres a.s.l., lithological description, carbonate content (10% HCl), MUNSELL colours and faunal remains. MUNSELL colours: 10YR 2/1, black; 10YR 2/2, very dark brown; 10YR 3/1, very dark grey; 10YR 3/2, very dark greyish brown; 10YR 3/3, dark brown; 10YR 4/1, dark grey; 10YR 4/2, dark greyish brown; 10YR 4/3, brown; 10YR 4/4, dark yellowish brown; 10YR 5/1, grey; 10YR 5/2, greyish brown; 10 YR 5/3, brown; 10YR 6/1, grey; 10YR 6/2, light brownish grey; 10YR 6/3, pale brown; 10YR 6/4, light yellowish brown; 7.5YR 2.5/1, black; 7.5YR 2.5/3, very dark brown; 7.5YR 4/2, brown; 5YR 4/6; yellowish red; 5YR 3/4, dark reddish brown.

Table S2. Animal species, part of the skeleton documented by bones and archaeological evidence related to the respective sediment block.