

Human-environmental relationships in the Early Iron Age recorded in a dark buried (anthropo-)soil from Ostrowite archaeological complex in northern Poland

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ABSTRACT

This study gives insights into natural factors and human impact that affected a dark soil formation at the Ostrowite Archaeological Complex (northern Poland) during the Early Iron Age (8th–7th centuries BCE). In this period, the area was occupied by settlers of the Early Pomeranian culture (so-called *Wielka Wieś Phase*). Despite abundant archaeological and paleoenvironmental research in Europe, geoarchaeological investigations on paleosols using palaeoecological analysis, including micromorphology and molecular markers, still remain limited in N Poland. A multidisciplinary approach was applied, combining geochronology, geochemistry, sedimentology, palaeobotany, and soil micromorphology. Results indicate a long-term transition from natural to anthropogenically modified soils. Land use traces are linked to mixed agricultural and farming practices. Multi-proxy data revealed evidence of shifting cultivation, crop cultivation (millet and wheat), and livestock husbandry (cattle, sheep, and goats) supported by a fallow rotation system. Overall, the findings highlight how Early Iron Age communities managed their economic practices in the recently glaciated zone, formed mostly by tilly and sandy relief forms. We deliberate land-use strategies such as forest clearance, crop farming, and pasture

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management on the surface of an undulating moraine plateau with numerous small, closed depressions after melted ice blocks. This research demonstrates the high interpretative value of buried soils for reconstructing past human-environment interactions and economic practices in N Poland.

1. Introduction

The presence of vestiges of former agricultural landscapes is a common occurrence in Europe, as humans have exerted a profound influence on their environment since the advent of agriculture (Groß et al., 2019; Makohonienko et al., 2023). More pronounced human impact on European lowlands was related to the “Neolithic revolution” (Bogucki & Grygiel, 1993; Bogucki, 1996) and the mid-Holocene climatic optimum, when vegetation cover and density changed dramatically, accompanied by the proliferation of archaeological artifacts (Zolitschka et al., 2003). Since then, increasing human activity – including deforestation, land use changes, and accelerated erosion – has repeatedly left a stratigraphic imprint: Buried paleosols overlain by slope-derived deposits are widespread in the surroundings of archaeological sites (Twardy, 2011; Kittel, 2014, 2015; Karasiewicz et al., 2014).

Paleosols serve as crucial geoarchaeological archives preserving pedogenic, botanical, and geochemical signatures of past environments, land use practices, and climatic conditions (Goldberg & Macphail, 2006; Sheldon & Tabor, 2009; Pietsch & Kühn, 2017; Kaiser et al., 2020). The Ostrowite Archaeological Complex (OAC) in northern Poland offers a particularly valuable case study: its paleosols date to the Early Iron Age (EIA, ca. 8th century BCE) and thus record the environmental footprint of Pomeranian Culture communities. This period marks a pivotal transition from the Late Bronze Age (LBA) to EIA and the introduction of iron tools, especially in agriculture which catalysed significant socio-economic and ecological changes (Urbańczyk, 2020; Niedziółka & Święta-Musznicka, 2023).

Decades of archaeological research in northern Poland have elucidated prehistoric human-environment interactions from the EIA to the Middle Ages (Kabaciński et al., 2009; Dziegielewski, 2010, 2016; Dziegielewski and Przybyła, 2024; Sikora et al., 2017). Recent studies have proven the potential of multi-proxy studies for the reconstruction of past land use (e.g., crop farming, livestock breeding) (Kittel, 2016; Krupski et al., 2022), thereby also understanding how human activities played a role in the formation of terrestrial archives (cf. Golyeva et al., 2018; Scherer et al., 2021; Brönnimann et al., 2024; Tomé et al., 2024a, Tomé et al., 2024b).

Despite the OAC is one of the best-documented multi-period record, geoarchaeological and paleoenvironmental research remain limited in northern Poland, especially regarding the reconstruction of subsistence strategies during the EIA.

To address this gap, this study applies a multi-proxy approach to EIA paleosols at OAC, aiming at (i) identifying environmental and anthropogenic factors for paleosol formation; (ii) reconstructing EIA land-use practices and their impact on landscape transformation. We integrate conventional geochemical (pH, element contents) and paleoenvironmental proxies (micromorphology, pollen, phytoliths) with vegetation – and crop-specific biomarkers including *n*-alkanes, miliacin, 5-*n*-alkylresorcinols (AR) and faecal lipid biomarkers (bile acids, 5- β -stanols).

To guide this investigation, we tested the following hypotheses:

- i. Forest clearance during EIA is recorded as declines in arboreal pollen (e.g., *Quercus*, *Alnus*), long-chain *n*-alkanes and charcoal, coupled with increased coarse colluvial deposits in EIA sedimentary horizons, indicating human-induced slope erosion.
- ii. Mixed agropastoral economy is reflected in: millet cultivation evidenced by miliacin and characteristic phytoliths; wheat cultivation indicated by cereal-type pollen, long-chain *n*-alkanes and ARs; livestock husbandry recorded by elevated faecal biomarkers.

2. Geographical setting

The OAC is located at 53°38'53.9"N and 17°39'23.1"E in Eastern Pomerania (N Poland) (Fig. 1A), within the Northern Krajna Lakeland (Mesoregion ID: 314.69) near the southern edge of the Charzykow Plain and the eastern part of the Tuchola Forest Plain (Solon et al., 2018). The area is a plateau between the Gwda and Brda river valleys. Moraine plateaus, glaciofluvial plains, together with accumulation moraines, kames, eskers, and tunnel valleys, are the dominant landforms in the area. The glaciofluvial sands are the parent material for the formation of podzolic soils, partially under forest cover, as well as Cambisols and Luvisols with varying degrees of clay illuviation (Tołoczko, 2020). At the hilltop positions, truncated Cambisols and Luvisols as well as Leptosols are widespread and associated with their colluvic counterparts in foot slope position (IUSS Working Group WRB, 2022).

The main part of the settlement complex is located between 140 and 142.5 m a.s.l. on a N-S-oriented hump of a moraine plateau, approximately 9 km southeast of Chojnice town and 1.5 km northeast of the modern Ostrowite village. It is situated on the shore of Ostrowite Lake (Sikora et al., 2017) (Fig. 1B, C). Quaternary deposits from the Pleistocene and Holocene cover the entire area. The relief is primarily shaped by young glacial landforms, including glacial, glaciofluvial, and limno-glacial features, formed during the retreat of the Weichselian ice sheet (Kittel et al., 2025). Geologically, the OAC area is composed of glacial tills, gravels, and sands that serve as the parent material for soil formation (Długosz-Lisiecka et al., 2022). The soils at the OAC are classified as a subtype of Mucky Black Soils within the Black Soils group according to the Polish Soil Classification (*Systematyka Gleb Polskich*, 6th edition), which corresponds to Gleysols or Histic Gleysols according to the World Reference Base (IUSS Working Group WRB, 2022).

The soil profile analysed in this study—hereafter referred to as OSWG1—is located near a former analysed core taken from a kettle hole (OST1), approximately 250 m northeast of the OAC and about 400 m from Lake Ostrowite (Kittel et al., 2025). The depression lies within a hummocky moraine plateau formed during the Weichselian glaciation. The OST1 core, situated at 133.7 m a.s.l., was collected from the deepest part of the kettle hole. The OSWG1 trench lies 65 m west of OST1, within the same paleobasin system near the basin margin (Fig. 2). The modern terrain surface in the area of OSWG1 trench is elevated up to 135.8–139.0 m a.s.l.

3. Archaeological characteristics

3.1. Regional background: Early Iron Age in Pomerania

The EIA in N Poland is associated with the emergence of the Pomeranian Culture (PC) during the 9th and 8th c. BCE. Originating in Pomerania, the PC expanded into Greater Poland, Silesia, and Central Poland by the 5th–3rd c. BCE (Dziegielewski, 2010). The *Wielka Wieś* Phase (Hallstatt C, 8th–7th c. BCE) marked a transitional stage between Lusitan (Middle to Late Bronze Age) and Pomeranian traditions. It was characterized by long-term, stable settlements—often on sandy or clayey soils near peat bogs (Kittel, 2005).

In the vicinity of OAC several LBA (Period V) burial sites are known. The best-documented are Leśno Site No. 2a and Leśno Site No. 2 (Walenta, 2008), the latter a distinct barrow cemetery. Outside the Leśno micro-region, flat cemeteries occur at Łęg Kolonia (Górska-Grabarczyk, 2000, 2002), Nowy Młyn, Stupy (Grabarczyk, 1992) and Lotyń (Trzciński, 1997a). Only a relatively few settlements from this period are known. Most of these are from Walenta's (2008) who surveyed the

Leśno settlement micro-region about 30 km NE of OAC. Outside that micro-region, additionally sites were identified during investigations of early medieval fortifications. One of them is the Lusatian culture hillfort, or hilltop settlement, at Raciąż (approximately 8 km northeast of OAC), which was later reoccupied as a fortification in the early Middle Ages

(9th–10th century CE) and finally transformed into a timber castle in the 13th century CE (Sikora & Trzcíński, 2013). A similar pattern can be seen at the Lusatian Culture settlement at Charzykowy (Wilke, 1969), which is located around 15 km north-west of OAC. This site was used in the early Middle Ages (8th–10th century CE) as a hillfort, although it is

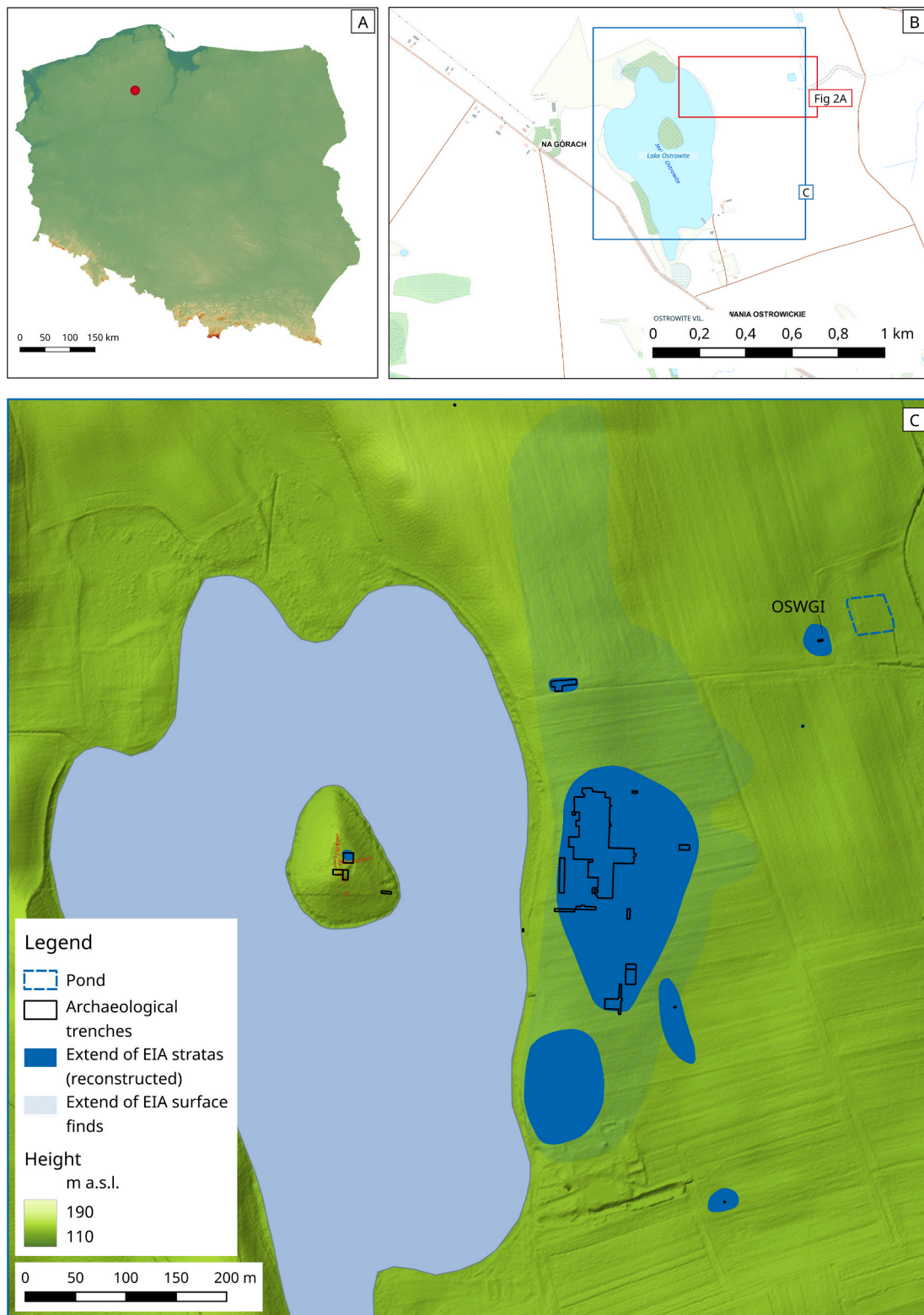


Fig. 1. Situation of the Ostrowite Archaeological Complex (OAC) and OSWGI trench: A. Location of study area in Northern Poland; B. Topographic map of the immediate surrounding of Ostrowite Lake and its proximity to OAC; C. Digital Terrain Model of the area of OAC with the reconstructed extend of the Early Iron Age settlement based on archaeologically localised stratigraphic units and distribution of surface finds.

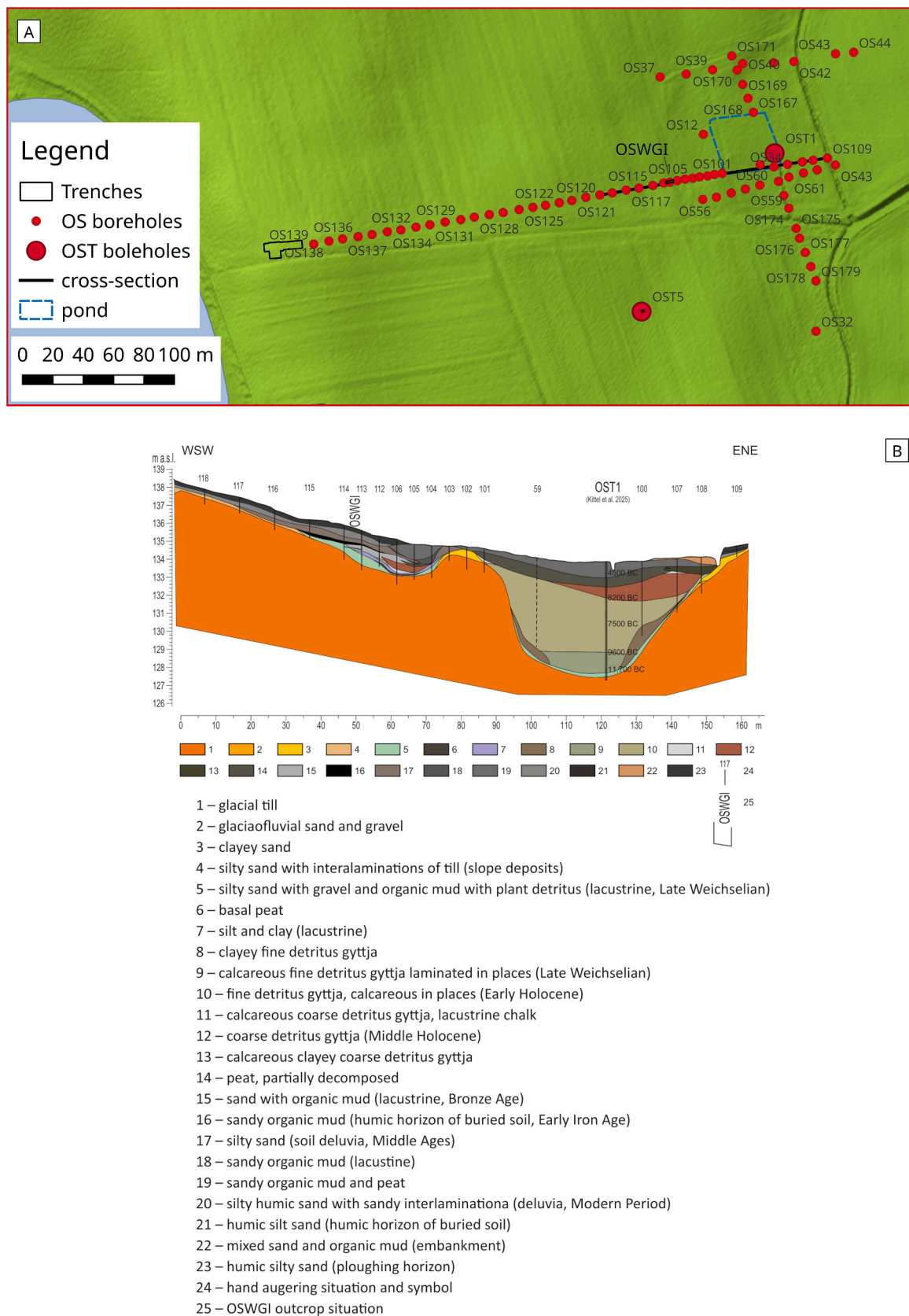


Fig. 2. Cross-sections performed for geoarchaeological investigations: A. Localisation of geoarchaeological sampling on the background of Digital Terrain Model; B. Geoarchaeological cross-section of the OST1–OSWGI transect showing terrain elevation, stratigraphic units, and archaeological horizons.

unclear whether it was fortified during the LBA or EIA. In contrast, Obrowo No. 1 (ca. 8 km south-east of OAC) clearly shows evidence of EIA fortification, which was radiocarbon dated to 750–416 BCE (68.3% probability, lab. code MKL-2531) and 893–593 BCE (68.3%, MKL-2532). This confirms its origin in the LBA–EIA period. The site was later reused and rebuilt in the EMA (Wilke 1972; unpublished research by J. Sikora).

LBA hoards of bronze ornaments and ingots are common – found at Charzykowy, Rytel (Rząska and Walenta, 2017), in Krępsk (Sprockhoff, 1956) and Ostrowite. None ^{14}C dated – mostly discovered accidentally or via metal detecting, without proper excavation. Further Kaliska I hoard (ca. 45 km NE of OAC) (showing some similarities in the set of deposited objects e.g. kidney-shaped bracelet), dates to 790–740 BCE (Kaczmarek et al., 2022); Kaliska II to 830–750 BCE (Szczurek & Kaczmarek, 2022).

The *Wielka Wieś* Phase settlement near OAC is best known for its burial sites, which resemble the one found in Ostrowite. Similar cist graves, constructed from local erratic stones and containing distinctive lidded urns, have been discovered at the Orlik, Małe Gliśno and Leśno site no. 22 (Walenta, 1996, 2008, 2010) as well as at Gockowice (Trzciński, 1997b) and Chojnaty (Rzepecki & Walenta, 2009). The latter contains a series of radiocarbon dates that suggest an interval between 800 and 670 BCE for the site's chronology (Rzepecki & Walenta, 2009). Settlement sites from this period are much less well known. Apart from the Ostrowite site, only the Chojnaty and Czarnoszyce sites have been subject to archaeological research (Rzepecki & Walenta, 2009; Janiak et al., 2022).

PC communities likely organised socially around autonomous, extended-family units, following a segmentary model. Settlements expanded into coastal, uplands, and riverine zones, later concentrating spatially as surrounding land was cleared for agriculture – evidenced by storage pits pottery fragments and cereal grains. In later EIA eastern Pomerania, demographic growth is reflected in rising number of burial ground numbers (Łuka, 1971, 1975, 1983, 1985; Malinowski, 1989).

3.2. The Ostrowite Archaeological Complex (OAC)

The area of OAC comprises several archaeological sites, including Lake Ostrowite Island, a submerged site, the eastern lakeshore, and dispersed finds extending further inland. The island preserves relics of a Medieval settlement (11th–14th c. CE), with limited evidence of EIA occupation. The eastern shoreline (ca. 25 ha) contains an almost continuous sequence of archaeological phases: Late Palaeolithic and Mesolithic (10,000–5,500 BCE), Early Neolithic (5,200–5,000 BCE), LBA and EIA (850–550 BCE), Roman Period and Migration Period (1st–5th c. CE), and the Middle Ages (11th–14th c. CE). Scattered finds from the 15th–20th c. AD were recovered during metal detector surveys. The underwater site reveals Medieval timber bridges (11th–13th c. CE). Pottery stray finds relate to EIA, Roman, Medieval, and Modern occupation (Sikora et al., 2017, 2019).

EIA finds are concentrated in the southern and central parts of the eastern lakeshore. Most features are shallow postholes (10–15 cm), poorly preserved due to later disturbance and erosion, and rarely attributable to structures such as houses or fences. Additional features include storage and waste pits, hearths, and large vessels set into the ground (usually preserved only as base fragments). Charcoal from hearth Feature No. 279 was dated to 986–764 BCE (68.3%; 2670 ± 100 BP, lab. code: MKL-3534).

EIA features were sealed beneath grey or brownish-grey humic silty sand. Parallel EIA-bearing layers were identified in separate sondages, ranging from a few centimetres to 41 cm in thickness. These layers consistently overlay EIA features and were later cut by Roman and Medieval intrusions. Their contents are dominated by EIA pottery sherds and flints, with rare Roman material likely introduced through bioturbation.

A small EIA cremation cemetery comprising six stone cist urn burials

was identified in the central part of the eastern shore settlement. Two graves were partially destroyed by Medieval burials (from 11th–12th c. CE), one was cut by a Medieval pit and further damaged by ploughing, resulting in fragmented urns. Notably, two EIA urns with cremated remains were redeposited in the basal fill of a Medieval pit, indicating disturbance during 12th c. CE earthworks. Magnetic survey suggests additional, unexcavated graves east of the trench (Sikora & Wroniecki, 2014). In total, only seven EIA cremation burials have been identified (including two from a secondary Medieval waste pit), while geophysical data indicate a further 6–8 possible graves. This small number suggests a limited settler group, contrasting with the extensive EIA settlement evidence at OAC, and leaves open the possibility of additional contemporaneous cemeteries in the area.

In 2022, a metal-detector survey in the northern part of Site No. 2 revealed a Bronze Age hoard comprising bracelets, epaulets, buckle/brooch fragments, and a copper-alloy ring (possibly a small bracelet or bridle element). The assemblage dates to the 5th Bronze Age Period and is broadly contemporaneous with the EIA settlement, although its connection to the *Wielka Wieś* Phase remains uncertain.

Non-invasive surveys conducted in 2012 and 2017, combined with surface survey finds and geophysical prospection, indicate that the EIA settlement covered approximately 10 ha. Additional evidence from Lake Ostrowite Island includes scattered EIA pottery (residual and redeposited in Medieval layers) and one partially destroyed EIA feature truncated by later activity. This suggests limited *Wielka Wieś* Phase occupation, likely linked to lake-resource exploitation.

4. Methods

4.1. Fieldwork and sampling strategy

The exact location of the excavation was based on previous geological and cartographic mapping of the archaeological complex. Additionally, a series of corings was conducted across the area, which allowed the identification and spatial distribution of buried soil horizons. Based on these results, the final location of the excavation and sampling transect was selected.

A hand-held Eijkelpkamp geological auger equipped with a gouge sampler was used to collect 60 drillings to obtain an overview of the geological and edaphic setting of the depression and its surroundings (Fig. 2). To obtain detailed information on the buried soil, slope cover, and geological features documented in the shore zone of an organic deposit basin, a 1×5 m outcrop was excavated at a footslope position. Within each 10 cm arbitrary layer, stratigraphic units were distinguished, and all excavated deposits were sifted stratum by stratum using a 4×4 mm sieve. This way, applying the archaeological method of exploration (cf. Kittel, 2014; Kittel et al., 2018a, Kittel et al., 2018b), all artifacts (mostly potsherds) and ecofacts (bones) were collected and attributed with relation to arbitrary layers, as well as to stratigraphic units (Fig.S1;S2).

The artifacts underwent archaeological, chronological, and cultural analysis, the results of which were utilized to determine the age of the units. The bones were subjected to basic archaeozoological analysis, and a few of them were selected for radiocarbon (^{14}C) dating.

All soil samples were collected during the fieldwork operations in August 2021 and from a partly reopened trench in September 2023.

In 2021, samples for sedimentological and geochemical analyses were collected throughout the entire profile (0–115 cm below ground level (b.g.l.)). From 0 to 70 cm and from 95 to 115 cm, samples were taken at 5 cm intervals (0–5, 5–10 cm). Between 70 and 95 cm, higher-resolution sampling was applied at 2 cm intervals (70–72, 72–74, ..., 90–92, 93–95 cm). The samples for pollen, plant macrofossils, phytolith and palaeozoological analyses were collected from 2 to 105 cm depth, with a standard 5 cm resolution within 5–70 and 95–105 cm, and 2 cm resolution between 70 and 95 cm b.g.l. Biomarker samples were obtained between 65 and 95 cm at 5 cm resolution. Additionally, a

monolith from 50 to 100 cm depth was collected for micromorphological study into the metal box $10 \times 10 \times 5$ cm.

In 2023, six undisturbed monoliths were collected for micromorphological analysis from the following depth intervals: 94.5–88.5 cm, 93–85 cm, 83.5–74.5 cm, 78–69 cm, 53.5–44.5 cm, and 39–30 cm. Additional samples for geochemical and sedimentological analyses were taken from 25–100 cm depth at 5 cm resolution. Samples for plant macrofossil analysis were collected also between 65 and 95 cm, also at 5 cm resolution. Three selected plant macrofossil samples were dated using accelerator mass spectrometry (AMS) from depths of 65–70, 70–80, and 85–90 cm. Three OSL samples were collected; however, only one from 90 cm b.g.l., taken with a 4×5 cm steel cylinder, is discussed here. Additional dose-rate material was collected from slope deposits at 33 and 49 cm b.g.l. (Fig. 3; Table S2). The values shown on the vertical scale in Fig. 3 represent elevations in metres above sea level (m a.s.l.).

4.2. Chronological, sedimentological and geochemical characterisation

Radiocarbon (^{14}C) measurements were performed at the Laboratory of Absolute Dating (Krakow, Poland) using the protocols of Krapiec et al. (2018) and Cherkinsky et al. (2010). Calibrated ages (BCE/CE) were calculated using IntCal20 (Reimer et al., 2020) in OxCal 4.4.4 (Bronk Ramsey, 2009).

Optically stimulated luminescence (OSL) dating was applied to quartz grains. Equivalent doses assessed via OSL (Risø TL/OSL DA-20 reader 6 mm Hoya U-340 filter, $^{90}\text{Sr}/^{90}\text{Y}$ beta source) using SAR protocol (Murray & Wintle, 2000). Dose rates were assessed via radioactivity in gamma-rays spectrometry using High-Purity Germanium (HPGe) detector (Canberra Indust., Lingolsheim, France) (^{238}U , ^{232}Th , ^{40}K activities) and calculated online with Tudyka et al. (2022) conversion factors, assuming $15 \pm 5\%$ water content. Quartz grains ($125\text{--}200\text{ }\mu\text{m}$) were isolated via $\text{HCl}/\text{H}_2\text{O}_2$ treatment, Na-polytungstate separation (2.62 to 2.75 g/cm^3), and HF etching. The final equivalent dose (De) values were derived using the Central Age Model (CAM, Galbraith et al., 1999) in R package ‘Luminescence’ (Kreutzer et al., 2020).

Grain size distribution was measured by laser diffraction (Master-Sizer 3000, Malvern, Worcestershire, UK) (Institute of Geography and Spatial Organization PAS, Krakow). The organic matter was removed with $30\%\text{ H}_2\text{O}_2$ prior to analysis. Data were processed to obtain Folk & Ward's (1957) sedimentological indices – mean grain size in the phi scale (M_z), standard deviation (sorting σ_1), skewness (S_k), and kurtosis (K_g) – calculation were performed with Gradistat 5.11 (Blott & Pye 2001).

Soil pH was measured potentiometrically (glass electrode) in a 1:1.5 soil–water suspension. Total Organic Carbon (TOC, %) was determined with the Tyurin method. Carbonate were determined using the Scheibler

method (Shamrikova et al., 2022). Total C, nitrogen (N), and sulfur (S) were measured with a VarioMAX analyzer (Elementar, Langensfeld, Germany). Loss-on-ignition (LOI) was conducted at $550\text{ }^\circ\text{C}$ for 5 h constant weight (Hoogsteen et al., 2018). Ash was digested with 8 ml concentrated NH_3 , 2 ml $10\%\text{ HCl}$ and 2 ml of H_2O_2 in an Ethos UP microwave mineraliser (Milestone, Sorisole, Italy). Sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and lead (Pb) were determined by atomic absorption spectrometry (AAS) (iCE 3500, ThermoFisher, Waltham, USA). Total phosphorus (P) was quantified with a flow-injection analyzer (FIA) (MLE, Dresden, Germany).

Bulk density was measured on constant volume samples dried at $105\text{ }^\circ\text{C}$.

4.3. Micromorphology

Clean, leveled samples were collected in Kubiena tins. Solid blocks were impregnated with epoxy resin under vacuum to stabilise structure and fill voids (Nieuwendam et al., 2020). After hardening, slabs were cut into 10×10 cm with a diamond saw, ground flat, mounted on slides, and thinned to $80\text{ }\mu\text{m}$ (Leszczyńska & Jankowiak, 2021). Micromorphological analysis followed Nicosia & Stoops (2017), Stoops (2021), and Trombino & Verrecchia, (2021), using terminology by Fitzpatrick (1984).

4.4. Archaeobotanical characterisation

Five samples for plant **macro-remains** analysis of various volume ($1250\text{--}1300\text{ ml}$ for Units 4 and 3, ca. 15 ml for Unit 2 and basement deposits) were taken from the profile. Sample processing was performed using a sieve with a mesh diameter of $\varnothing = 0.18\text{ mm}$. After drying, the plant material was sorted under a stereoscopic microscope (ZEISS Stemi 508 stereomicroscope at $10\text{--}16\times$ magnifications) to select seeds, fruits, charcoal fragments, and vegetative plant fragments suitable for taxonomic identification. Only **charcoal fragments** were found. One charcoal fragment serves as an observation and count unit, examined in three anatomical sections of wood: A transverse, a longitudinal radial, and a tangential section was used for identification to the level of species, genus, or family, depending on its size, preservation, and anatomical characteristics. Due to limited diagnostic features, trees and shrubs in Central Europe are determined by the genus level (Schweingruber, 1990).

For **pollen** analysis samples of 1 cm^3 in volume were taken. Standard laboratory preparation with acetolysis method was implemented (Berglund & Ralska-Jasiewiczowa, 1986). To remove silica, the

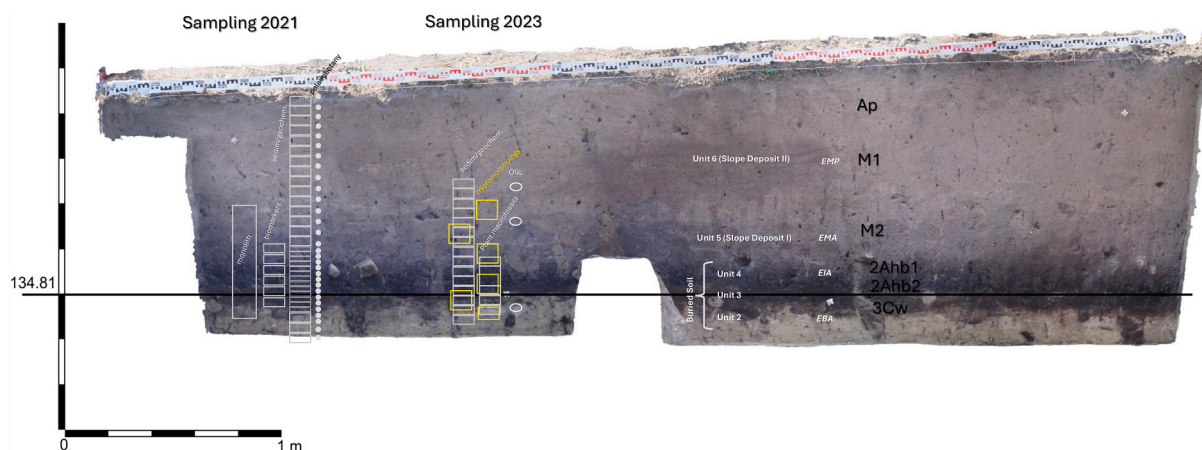


Fig. 3. Sampling strategy in the OSWGI trench. Abbreviations used in the figure: OSL – Optically Stimulated Luminescence; EBA – Early Bronze Age; EIA – Early Iron Age; EMA – Early Middle Ages; EMP – Early Modern Period.

sediment samples were kept in cold 40% hydrofluoric acid for 24 h. Palynological analysis was performed using an Olympus BX43 light microscope at 400x and 600x magnifications, followed by Moore et al. (1991) for pollen terminology. Due to the very low representation of sporomorphs, five preparations measuring 18 x 18 mm were studied under microscope for each sample. All microfossils encountered were counted. The results were presented in a diagram showing the numbers of pollen grains and spores recorded in samples. The data and diagram were produced with the use of Tilia software (Grimm, 1992).

For **phytolith** analysis, slides were examined with an Olympus BX51 TL RL optical microscope at 400 x magnification, and particles were identified and counted using a JEOL 6610LV scanning electron microscope. Morphological descriptions and nomenclature of phytoliths were grounded in the International Code for Phytolith Nomenclature (ICPN) 2.0 (International Code, 2019), and their biocenotic characteristics were defined following the approach of Golyeva (2007).

4.5. Lipid biomarkers

The analysis of **n-alkanes, steroids, and bile acids** followed the method of Birk et al. (2012) and Scherer et al. (2024). Samples were extracted via microwave-assisted extraction using dichloromethane/methanol (DCM:MeOH, 2:1, v/v). Extraction was performed with a Multiwave Pro (Microwave Reaction System Solv, Anton Paar GmbH, Austria). After extraction, internal standards (IS1) were added to the total lipid extract (TLE). Concentrated and dried TLEs were saponified at room temperature for 12–14 h using potassium hydroxide in MeOH. Liquid-liquid extraction was performed to separate *n*-alkanes and steroids from bile acids. Solid phase extraction (SPE) was performed to separate *n*-alkanes and steroids using deactivated silica gel. Carboxyl groups of bile acids were methylated with HCl in MeOH at 80 °C for 2 h and bile acids were purified with SPE using PE columns packed with activated silica gel. To ensure amenability to gas chromatography (GC), the polar fractions of steroids and bile acids were silylated. 5 α -cholestan-3 β -ol-d₄ was added as IS2 to all samples before analysis.

n-alkanes were quantified via flame ionization GC (GC-FID, Agilent, Santa Clara, CA/USA) with H₂ as carrier gas. Steroids and bile acids were analyzed via GC-mass spectrometry (GC-MS/MS) using a 7890B-Triple Quad 7000D (Agilent Technologies, Santa Clara, CA/USA). Data was acquired in selected ion monitoring (SIM) mode for quantification and in scan mode to verify peak identification. He (99.9999% purity) was used as carrier gas. Recovery was > 77% for all analyzed substances.

Cereal biomarker analysis (**miliacin, ARs**) followed the method by Scherer et al. (2025) with few modifications. Samples were extracted via Soxhlet using a Universal – Extractor (E-800, Büchi, Flawil, Switzerland) with DCM:MeOH (2:1, v/v). IS1^a (Methyl octadecenoate-d₃₅) and IS1^b (AR-18:0) were added as IS1. TLEs were concentrated at 50 °C for 15 min and transferred to storage vials, which were kept in the freezer at –20 °C until further analysis. To ensure amenability to GC, TLEs were silylated. An injection standard (200 μ L of ca. 10 ng μ L⁻¹ IS2, *n*-octacosane) was added to each sample. Samples were analysed by GC-MS/MS using a 7890B-Triple Quad 7000D. A detailed version of the method description including information on used chemicals and technical settings is given in the supplementary information.

4.6. Archaeozoology

The collection of **bone** remains obtained during the OSWGI trench excavation was subjected to taxonomic and osteometric analysis. Bone measurements were performed according to von den Driesch (1976). Animal age was determined based on the degree of ossification of the epiphyses of long bones and their diaphysis, as well as **tooth** wear (Lasota-Moskalewska, 1997, Lutnicki, 1972). Height at the withers (WH) was determined only for cattle, taking into account the V.I. Calkin, 1970. When it was impossible to determine the species affiliation of bone remains from small ruminants, sheep and goat, they were

described collectively as sheep/goat. Difficulties in distinguishing these species resulted from their high similarity and the lack of complete bones (Lasota-Moskalewska, 1997). Measurement values are given in mm.

5. Results

5.1. Pedostratigraphy and sediment units

The OSWG1 profile comprised a sequence of stratified units formed by both natural and anthropogenic processes. From top to bottom, the sequence included a modern ploughing horizon (Ap, 0–30 cm) followed by two horizons of slope deposits (M1, 30–50 cm; M2, 50–70 cm) that corresponded to the archaeological units 6 and 5. Together with the archaeological artefacts recovered from these horizons (Tab. S1), they resulted from human-induced soil erosion and could be classified as colluvial horizons (*German: Kolluvium*) according to German soil classification system (Ad-hoc-AG Boden, 2005; Kadereit et al., 2010). In M2, weak post-sedimentary pedogenesis was indicated by patchy cambic features and increasing levels of iron compared to overlying horizons, likely accompanied by a higher abundance of secondary iron oxides. The buried soil consisted of two horizons enriched in soil organic matter (2Ahb1, 70–80 cm; 2Ahb2, 80–86 cm) covering the parent material made of silty sands with organic matter interlamination and glacial till and sands (2Cw, 86–100 + cm). The buried and organic rich soil horizons (archaeological units 4 and 3) likely developed from former peatlands and were genetically related to the modern Mucky Black Soils that are widespread in Poland (Systematyka, 2019 *Gleb Polskich, 6th edition*). Numerous artefacts and ecofacts (e.g., potsherds, bones) and strong reworking of the horizons (EIA potsherds) indicated intensive anthropogenic imprint. The soil is classified as Solimovic Regosol (Panpaic, Archaic) according to WRB (IUSS Working Group WRB, 2022) (Table 1).

Unit 2 (86–96 cm; corresponds with stratigraphical unit 2231 in the archaeological documentation).

Silty sands with organic matter interlamination and frequent pebbles; light brown (10YR 7/3); compact. It contained more than 20 animal bone fragments. One, probably redeposited, EIA pottery fragment was found in this unit. Abundant molehill traces were visible in this layer. The lower boundary was indistinct, merging into the parent material. In the further result and discussion sections, we focus on the horizons of the buried soil.

Unit 3 (80–86 cm; corresponds with stratigraphical unit 2230 in the archaeological documentation) – humic horizon of Buried Soil.

Humic silty sand; very dark greyish brown (10YR 3/2); compacted and moist. This horizon included a dozen EIA potsherds, and a few bone fragments. The boundary with the underlying unit was gradual and smooth.

Unit 4 (70–80 cm; corresponds with stratigraphical unit 2229 in the archaeological documentation) – reworked humic horizon of Buried Soil.

Sandy organic mud; black (10YR 2/1); dense, compact, moist; likely anthropogenically reworked humic soil horizon. Molehill traces were also visible. It contained abundant strongly weathered EIA potsherds, strongly defragmented animal bones, daub fragments, single charcoal fragments, and numerous small stones. Part of the pebbles was also weathered. The layer lay horizontally at the elevation of ca. 134.9 m a.s.l. The lower boundary with Unit 3 is sharp and distinct.

Unit 5 (50–70 cm; corresponds with stratigraphical unit 2228 in the archaeological documentation) – Slope Deposit I.

Humic silty sand; greyish brown to grey (10YR 5/1); compacted; slope wash origin. This horizon included only numerous potsherds (one Early Medieval fragment) and animal bones (incl. tooth) fragments. The lower boundary with Unit 4 was sharp and distinct.

Unit 6 (30–50 cm; corresponds with stratigraphical unit 2227 in the archaeological documentation) – Slope Deposit II.

Silty sands with interlamination of fine sand; light brownish grey

Table 1

Physiochemical soil characteristics of the OSWGI profile, presented as horizon-wise means. Horizons classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022); M horizons denote colluvial horizons (from Latin migrare, “to migrate”) following to the German soil classification systems (Ad-hoc-AG Boden, 2005); AU: Archaeological unit referenced in this study; n: number of samples; Colours: Munsell soil colour code; CaCO₃: Calcium carbonate; TOC: total organic carbon.

Horizon	AU	Depth	n	Colour	Sand Silt Clay	pH _{H2O}	CaCO ₃	TOC
		[cm]			-----[%]-----		-----[%]-----	
Ap	—	0 – 30	1	n.d.	41 57 2	7.0	0	1.3
M1	6	30 – 50	4	10YR 6/2	42 56 2	7.0	< 0.1	1.3
M2	5	50 – 70	4	10YR 5/1	46 50 4	7.1	< 0.1	1.8
2Ahb1	4	70 – 80	2	10YR 2/1	29 64 7	6.7	< 0.1	5.3
2Ahb2	3	80 – 86	1	10YR 3/2	44 48 8	6.9	< 0.1	1.2
3Cw	2	86 – 100+	3	10YR 7/3	63 32 5	7.0	< 0.1	0.3

Table 2

Radiocarbon dating results for indeterminate charcoal from the OSWGI profile. All dates calibrated using OxCal v4.4.4 (Bronk Ramsey, 2009) with the IntCal20atmospheric curve (Reimer et al. 2020) and reported as calibrated years BP (cal BP) at 68.2% (1σ) and 95.4% (2σ) confidence. Laboratory codes are provided for traceability.

Depth[cm]	¹⁴ C age[yr BP]	cal. BCE/CE (1σ)	cal. BCE/CE (2σ)	Lab code
Unit 5 (M2), bottom of slope deposits				
65 – 70	1144 ± 21	882–972 CE	773–980 CE	MKL-A6508
Unit 4 (2Ahb1), buried soil				
70 – 80	2557 ± 27	796–596 BCE	803–567 BCE	MKL-A6509
Unit 2 (2Ahb2), sand with organic mud				
85 – 90	3675 ± 61	2140–1961 BCE	2275–1890 BCE	ETH-146667

(10YR 6/2); massive structure. Thin sandy interlaminations were slightly, sub-surficial inclined. These sediments were interpreted as likely deposited through slope wash processes. This unit contained only a small bone fragment and a flint flake. The boundary to the underlying horizon was diffuse and slightly wavy (Fig.S1; S2).

5.2. Geochronology

The ¹⁴C results allowed differentiation of three horizons according to their chronology: The oldest horizon corresponded to the lower-lying Unit 2 and was associated with the Early Bronze Age (85–90 cm; 2275–1890 BCE). The intermediate horizon was linked to the buried soil Unit 4 and related to the EIA (70–80 cm; 796–596 BCE). The youngest ¹⁴C age corresponded to the slope deposits of Unit 5 (65–70 cm; 882–972 CE). These results corresponded well with archaeological data, which indicated that the buried black soil (Unit 4) was used in the EIA by people of PC. It was subsequently covered by slope wash deposits (deluvia) formed during the Early Middle Ages (10th –11th c. AD) (Table 2).

One OSL dating originated from 90 cm depth (from deposits of Unit 2) yielded an estimated age of 14,210 ± 740 BP, corresponding to the Late Weichselian. This result demonstrated that the mineral fraction forming the parent material was repositied from older glacial deposits (aggregates) and was therefore not bleached. As the radiocarbon results directly dated organic remains associated with human activity, they were considered more reliable for the archaeological and paleoenvironmental interpretation of this layer (Unit 2). Therefore, the OSL age was not taken into account in further discussion (Table 3).

Table 3

Optically stimulated luminescence (OSL) dating results for deposits in Unit 2 (90 cm) of the OSWGI profile. Ages are reported in thousands of years (ka), measured relative to the year of sample collection (2023 CE). Three columns represent multiple independent measurements, while values in the brackets mean measurement uncertainty (error). Lab code is provided for traceability.

²³⁸ U _i	²³⁸ U	²³⁸ U	Dose rate	Equivalent dose	OSL age	Lab code
-----[Bq kg ⁻¹]-----			[Gy ka ⁻¹]	[Gy]	[ka]	
16.13 (59)10.59 (54)8.2 (18)	16.37 (63)11.44 (52)6.8 (20)	348 (23)321 (21)234 (18)	1.237 (57)	17.58 (43)	14.21(74)	GdTL-5491

5.3. Sedimentology

Underlying Sediments (below 100 cm). Mean grain sizes ranged from 3.6 to 4.4 ϕ, falling within the fine to very fine sand fraction. Sorting value ranged from 1.8 to 2.0 ϕ, with S_k around 0.1 and K_g values between 0.8 and 1.0. These deposits exhibited poor sorting, symmetrical distributions, and mesokurtic grain shapes. The grain size distribution showed a bimodal character, with alternating dominance of sand (26–75%) and silt (23–59%) across different depths. Clay remained a minor fraction (Fig. 4, Table S3, Table S4).

Unit 2 (86–96 cm). Compared to the underlying sediments, this unit exhibited slightly coarser grains and generally better sorting. Mean grain size ranged from 2.4 to 4.5 ϕ, indicating a dominance of fine sands to coarse silts. Sorting values (σ₁) ranged from 1.3 to 2.1 ϕ, while S_k varied between 0.1 and 0.5, suggesting distributions from symmetrical to coarse-skewed. K_g indicated leptokurtic distribution (range from 0.8 to 1.5). Notably, at a depth of 85–95 cm, the accumulation of coarser grains and better sorting was observed, with C/M diagram values falling within the IV/V segments, which similarly indicated coarser grain accumulation and improved sorting at this depth. The grain size distribution was unimodal, with a clear peak in the sand fraction, which dominated across all samples (52–80%). Silt was consistently present as the secondary fraction (20–45%), while clay content remained low (< 7%).

Unit 3 (80–86 cm). Mean grain size ranged from 4.3 to 4.6 ϕ, corresponding to very fine sand. σ₁ values ranged between 2.1 and 2.6 ϕ, indicating that the deposits were very poorly sorted, while S_k ranged from 0.2 to 0.4, showing a coarse-skewed distribution. K_g values indicated (0.8–1.07) leptokurtic grain size distributions. In comparison to

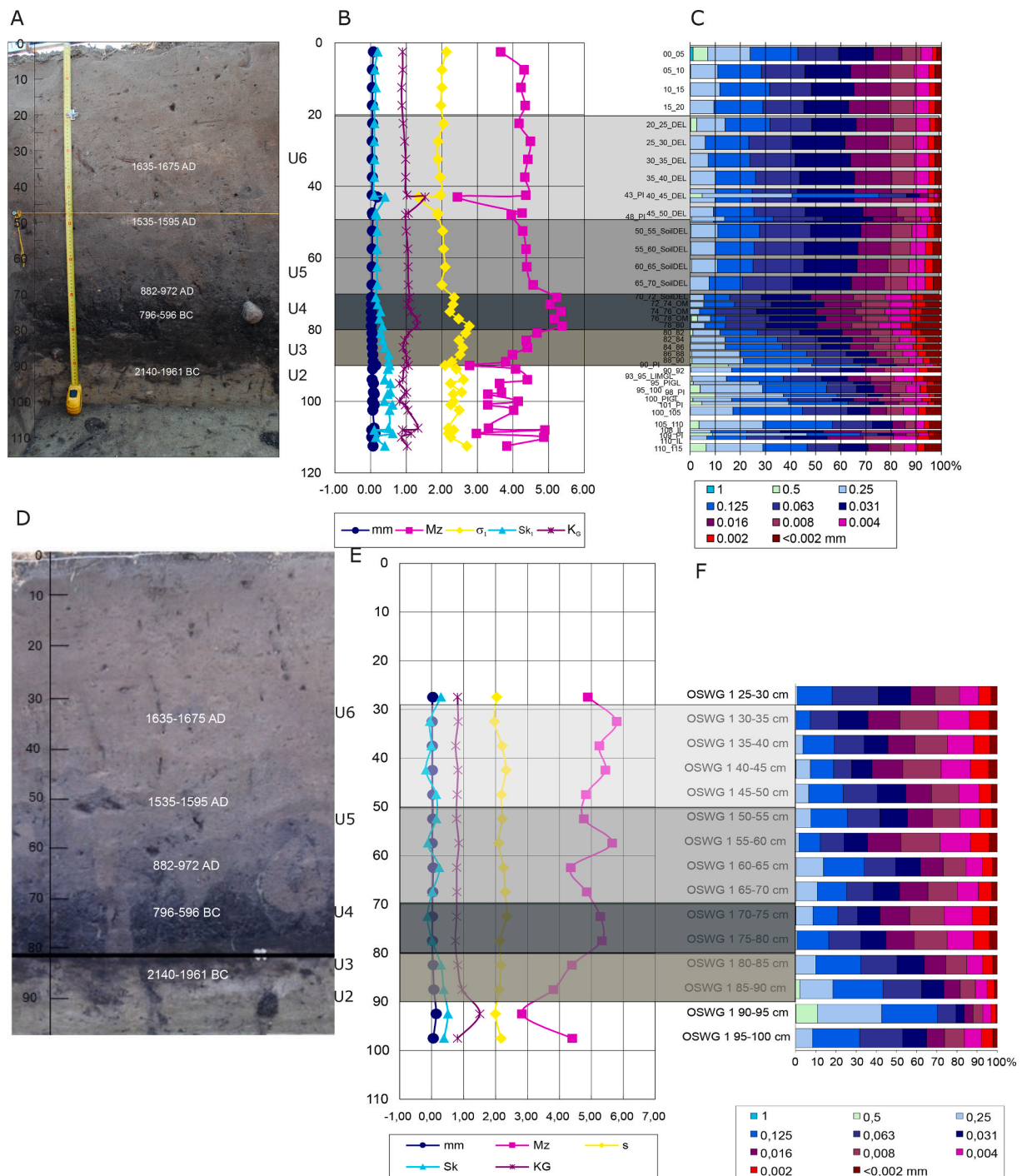


Fig. 4. (A) Outcrop of the OSWG1 profile excavated in 2021. (B) Grain-size parameters according to Folk and Ward (1957), including mean grain size (Mz), sorting (σ_1), skewness (Sk), and kurtosis (Kg). (C) Grain-size distribution of sediments in the OSWG1 profile, showing the relative proportions (%) of different size fractions. (D) Outcrop of the OSWG1 profile excavated in 2023. (E) Grain-size parameters according to Folk and Ward (1957), including mean grain size (Mz), sorting (σ_1), skewness (Sk), and kurtosis (Kg). (F) Grain-size distribution of sediments in the OSWG1 profile, showing the relative proportions (%) of different size fractions.

the underlying Unit 2, Unit 3 was characterized by finer mean grain size and notably poorer sorting; the S_k and K_g values showed slightly less variability than in Unit 2. Grain size distribution showed a unimodal to weakly bimodal character, with sand (44–52%) forming the dominant fraction and silt (41–48%) occurring in nearly equal proportions. Clay remained a minor fraction, ranging from 2% to 8%.

Unit 4 (70–80 cm) was characterized by mean grain sizes ranging from 5.0 to 5.3 ϕ , corresponding to coarse silts, in comparison to the underlying unit: σ_1 values indicated poor sorting, ranging from 2.1 to

2.7. S_k ranged from -0.1 to 0.3 and K_g values varied between 0.7 and 1.3 . Based on the C/M diagram, most samples from these units fell within sedimentary classes VI and VII. The grain size distribution was unimodal, with a clear peak in the silt fraction (58–66%), indicating that silt was the dominant component. Sand was present in subordinate amounts (approximately 27–32%), while clay remained a minor fraction ($< 10\%$).

5.4. Geochemistry

The carbonate content remained extremely low throughout the buried profile, with a maximum of 0.04%. The pH remained consistently neutral, ranging narrowly from 6.7 to 6.9, without notable fluctuations (Table S5; Table S6).

Total organic carbon (TOC) content reached its peak concentration in Unit 4, ranging between 4.3 and 6.2%. In the lower lying units, TOC decreased progressively, declining to 1.2% in Unit 3 and further to 0.2% in Unit 2. A similar trend was observed for loss-on-ignition (LOI). P contents were 4.7 mg/g d.w. (dry weight) in Unit 4, increased to 5.5 mg/g d.w. in Unit 3, and then decreased sharply to 0.4 mg/g d.w. in the underlying Unit 2. At a depth of 70–80 cm within the Unit 4, elevated levels of the following elements were observed: Ca 8.0–16.0 mg/g, K 1.6–2.6 mg/g, Fe 8.7–13.6 mg/g, Mn 0.2–0.4 mg/g, Cu 21.4–39.0 µg/g, Zn 21.2–25.6 µg/g. Additionally, an increased TOC/N ratio of 16.1 was noted, alongside with a slight rise in S concentration from 0.1% to 0.2%, compared to the underlying horizons. Clear variations were also

observed in the Fe/Mn (29.3–41.4) and Fe/S (4.4–10.6) ratios within this profile zone.

Bulk density values in Unit 4 ranged from 0.41 to 0.47 g/cm³, suggesting looser and more porous sediment rich in organic matter, in contrast to underlying layers. In Unit 3, bulk density increased to between 0.52 and 0.58 g/cm³, while in Unit 2 it ranged from 0.50 to 0.60 g/cm³, indicating more compacted sediment with comparatively lower organic content.

5.5. Micromorphology

Unit 2 (86–94.5 cm). The microstructure comprised a combination of intergrain microaggregates and locally massive areas. The coarse/fine (c/f) related distribution was predominantly enaulic to chitonic. Pedality was well developed, with well-separated aggregates. The micro-mass appeared undifferentiated under XPL. Porosity was moderately high, consisting of complex packing voids, channels, and occasional vughs. The coarse fraction was dominated by quartz grains, which were

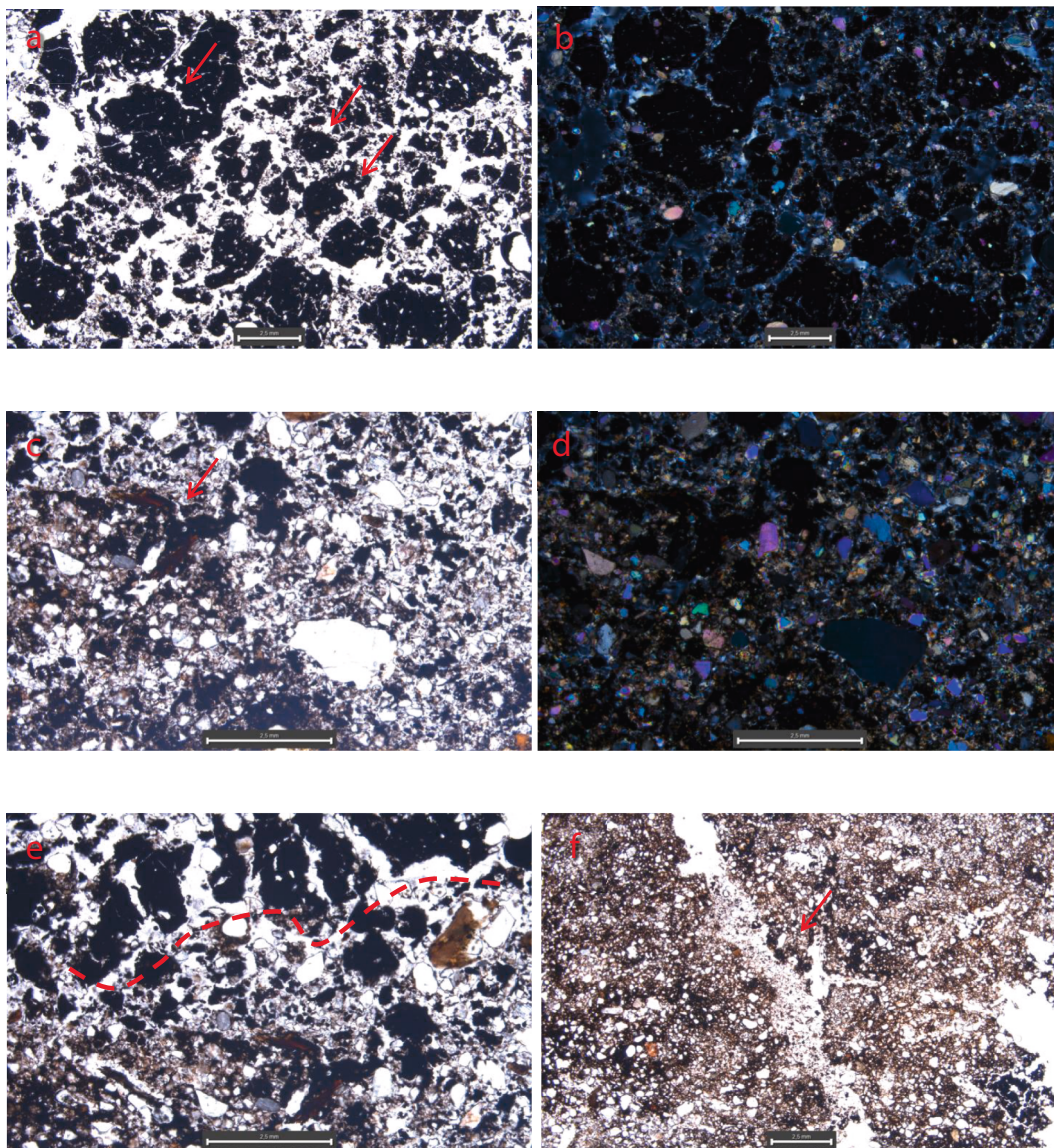


Fig. 5. Micromorphological features of OSWG1 soil horizons. A) Unit 4 under plane-polarized light (PPL) exhibits a complex microstructure with subangular blocks and crumb aggregates (red arrows) and well-developed pedality; B) the same field of view of Unit 4 under cross-polarized light (XPL). C) Unit 3 under PPL shows a weakly developed channel microstructure and a dense, undifferentiated b-fabric; some well-decomposed organic matter is present (red arrow); D) same field of view of Unit 3 under XPL; E) A sharp boundary between the anthropogenically altered Unit 4 and the non-altered Unit 3 is visible. F) Mineral infilling of coarse material in Unit 3.

poorly to moderately sorted, subrounded to rounded, and exhibited a random spatial distribution. Organic material was scarce, with only a few well-decomposed plant fragments observed. Weak pedofeatures in this horizon were indicated by few redoximorphic properties, such as depletion zones and iron-manganese nodules (Fig. 5; Table S7).

Unit 3 (80–86 cm). This unit displayed an intergrain microaggregate microstructure, with locally channel microstructure. The c/f related distribution ranged from enaulic to porphyric. Pedality was well developed, with aggregates showing good separation. The micromass remained undifferentiated. Voids were relatively abundant and included complex packing voids, channels, chambers, and occasional vughs. The coarse fraction consisted of poorly sorted, rounded quartz grains. Organic components included rare, well-decomposed wood and plant fragments. Mineral infillings were present and constituted the primary pedofeatures in this unit.

Unit 4 (70–80 cm). The microstructure was characterized by a combination of subangular blocky and crumb structures. Within the peds, the c/f related distribution was distinctly porphyric. Pedality was well developed, with clearly separated aggregates. The micromass was black and undifferentiated under crossed-polarized light (XPL). Voids were primarily composed of interconnected channels and chambers, both vertically and horizontally oriented and partially accommodating; with occasional planar voids. The coarse component consisted of poorly sorted, mostly rounded quartz grains that often appeared in clusters. Organic matter was present in the form of decomposed and amorphous residues. No coatings or distinct illuvial features were noted.

5.6. Plant macrofossils

Only charcoal fragments were identified as *Alnus* sp. and *Quercus* sp. These fragments did not exceed 2 mm in transverse section. They occurred in the upper layers (65–70 cm and 75–80 cm), associated with Unit 5 and 4, respectively. Other small and poorly preserved charcoal fragments were identified as broad-leaved trees or shrubs. From lower layers (between 80 and 95 cm) only one charcoal fragment was detected and which may have been due to the small sample size. No other plant remains were identified in this profile (Table 4). Consequently, only charcoal fragments could be selected for ^{14}C dating.

5.7. Palynology

Palynological analysis revealed very low amounts of pollen and plant spores, as well as more numerous fungal remains, wood cells, and algal microfossils (maximum 200 palynomorphs and up to 36 sporomorphs per sample). Palynomorphs were absent in only three samples above 95 cm, as well as in all samples collected below this depth. Despite low representation of sporomorphs, the fossil record provided hints for qualitative paleoenvironmental reconstruction. Based on the palynomorphs record, six pollen zones were indicated, showing stratigraphic changes in sediment composition, which may have reflected phases of environmental phenomena (Fig. 6). The bottom sample (Phase A-Unit 2) was devoid of sporomorphs, only wood cells and algal remains were noticed. Phase B (Unit 3/Unit 5) was characterized by the presence of Polypodiaceae spores and *Pinus* pollen. Trees were also represented by *Alnus* and *Betula* pollen, while herbaceous plants were represented by Cichorioideae, Brassicaceae, and Filipendula. Sphagnum and

Anthoceros punctatus spores were occasionally present. Samples from a depth of 85–75 cm were distinguished as subphase B1 based on higher amounts of Polypodiaceae and *Pinus*, and the high proportions of Betulaceae wood cells. Samples from a depth of 70–60 cm, which were poorer in palynomorphs, including a decrease in wood cells, were distinguished as subphase B2. This subphase represented the bottom-most part of slope deposits (Unit 5), covering the buried soils (Unit 4). In the B2 subphase, the proportion of spherical microfossils, most likely representing algae, increased. Phase C (Unit 5) represented sediments devoid of plant sporomorphs and fungal spores remains. However, abundant spherical algal microremains were present. Sporadic presence of pteridophyte spores and fungal spores, with a reduced proportion of spherical algal microremains characterized the phase D (Unit 6). *Pinus* and Betulaceae cells were also encountered. Phase E (within ploughing zone: 30–20 cm) was the most abundant in plant sporomorphs, fungal spores and hyphae. Pollen of trees *Pinus* and *Betula* was recorded in this horizon, accompanied by *Pinus* and Betulaceae wood cells. Herbaceous components were represented by Poaceae, Cichorioideae, Brassicaceae, and *Secale cereale* pollen. Spores of the hornwort *Anthoceros punctatus* and *Riccia* were recorded. Phase F (ploughing zone: 20–5 cm) showed the presence of *Pinus* and probably *Picea* pollen. Herbaceous plants were represented by Poaceae, Cichorioideae, and Brassicaceae. *Anthoceros punctatus* remains were still present. The proportion of fungal spores decreased, and no wood cells were found.

5.8. Phytoliths

The phytolith assemblages were heterogeneous, containing phytoliths from herbs, conifers, and both forest and meadow grasses present in almost all studied layers. Phytoliths of cultivated grasses (cereals) were identified in the buried soil layer at depths of 76–80 cm (Unit 4), alongside reed phytoliths at 76 cm. At depths of 78–82 cm, isolated sponge spicules exhibiting signs of corrosion were observed, suggesting redeposition processes. Phytolith concentrations were lower below 80 cm, whereas the upper horizons (up to 80 cm) showed higher abundance and greater morphological diversity (Fig. 7, Table S8, Table S9).

5.9. Fecal biomarkers

Unit 2 (86–96 cm) showed 5 β -stanol concentrations ranging from 33 ± 2.3 to $71 \pm 10 \text{ ng g}^{-1}$, with $\Sigma(\text{epi})\text{-}5\beta\text{-stigmastanol}$ values between 28 ± 3.8 and $62 \pm 2.9 \text{ ng g}^{-1}$. The HDCA/DCA ratio increased from 0.30 ± 0.04 at 85–90 cm to 1.0 ± 0.11 at 90–95 cm, while the DCA/LCA ratio varied from 11 ± 1.1 to 26 ± 18 . OEP values decreased from 3.9 to 1.5 . $\Sigma\text{nC}26\text{--nC}35$ concentrations declined from 930 to 270 ng g^{-1} , whereas the $(\text{nC}27 + \text{nC}29)/(\text{nC}31 + \text{nC}33)$ ratio varied between 1.4 and 1.9 . Miliacin concentrations were low ($24\text{--}25 \pm 6.6 \text{ ng g}^{-1}$), and ΣAR values ranged from 4.2 to $13 \pm 0.90 \text{ ng g}^{-1}$ (Table 5; Table 6).

Unit 3 (80–86 cm) was characterized by 5 β -stanol concentrations of $158 \pm 25 \text{ ng g}^{-1}$ and $\Sigma(\text{epi})\text{-}5\beta\text{-stigmastanol}$ values of $146 \pm 26 \text{ ng g}^{-1}$. The HDCA/DCA ratio was 0.17 ± 0.05 , while the DCA/LCA ratio reached 13 ± 1.2 . OEP was 4.2 , with $\Sigma\text{nC}26\text{--nC}35$ concentrations of 2635 ng g^{-1} and a $(\text{nC}27 + \text{nC}29)/(\text{nC}31 + \text{nC}33)$ ratio of 1.7 . Miliacin concentration was $89 \pm 23 \text{ ng g}^{-1}$, and ΣAR amounted to $16 \pm 2.3 \text{ ng g}^{-1}$.

Unit 4 (70–80 cm) showed 5 β -stanol concentrations ranging from

Table 4

Plant macrofossils from the OSWG1 profile.

Depth [cm]	<i>Fraxinus excelsior</i>	<i>Pinus sylvestris</i>	<i>Alnus</i> sp.	<i>Betula</i> sp.	<i>Quercus</i> sp.	<i>Salix</i> sp.	<i>Salix</i> sp./ <i>Populus</i> sp.	Deciduous
65 – 70	–	–	1	–	1	–	–	1
75 – 80	–	–	1	–	1	–	–	2
80 – 85	–	–	–	–	–	–	–	–
85 – 90	–	–	–	–	–	–	–	1
90 – 95	–	–	–	–	–	–	–	–

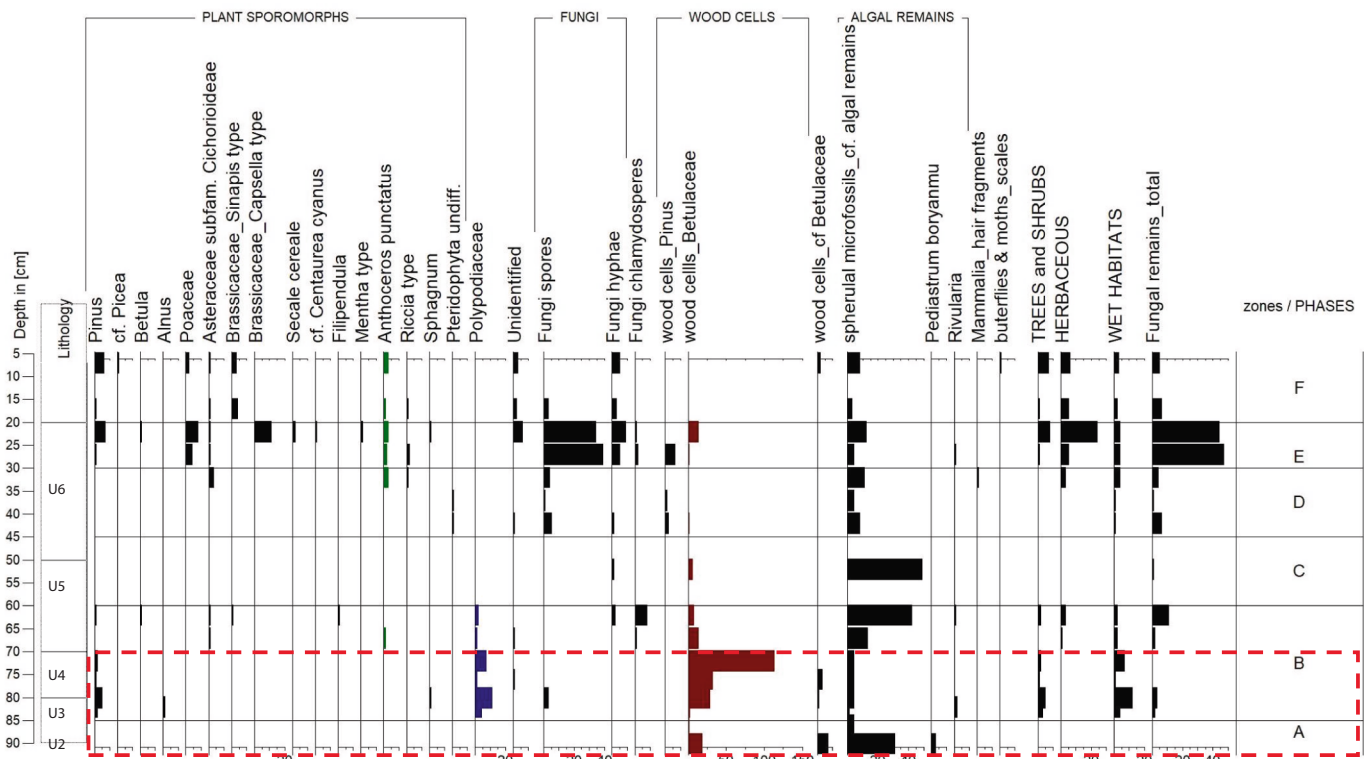


Fig. 6. Sporomorphs and non-palynomorphs record of the OSWG1 profile. Histograms represent an absolute content of recorded sporomorphs and NPPs.

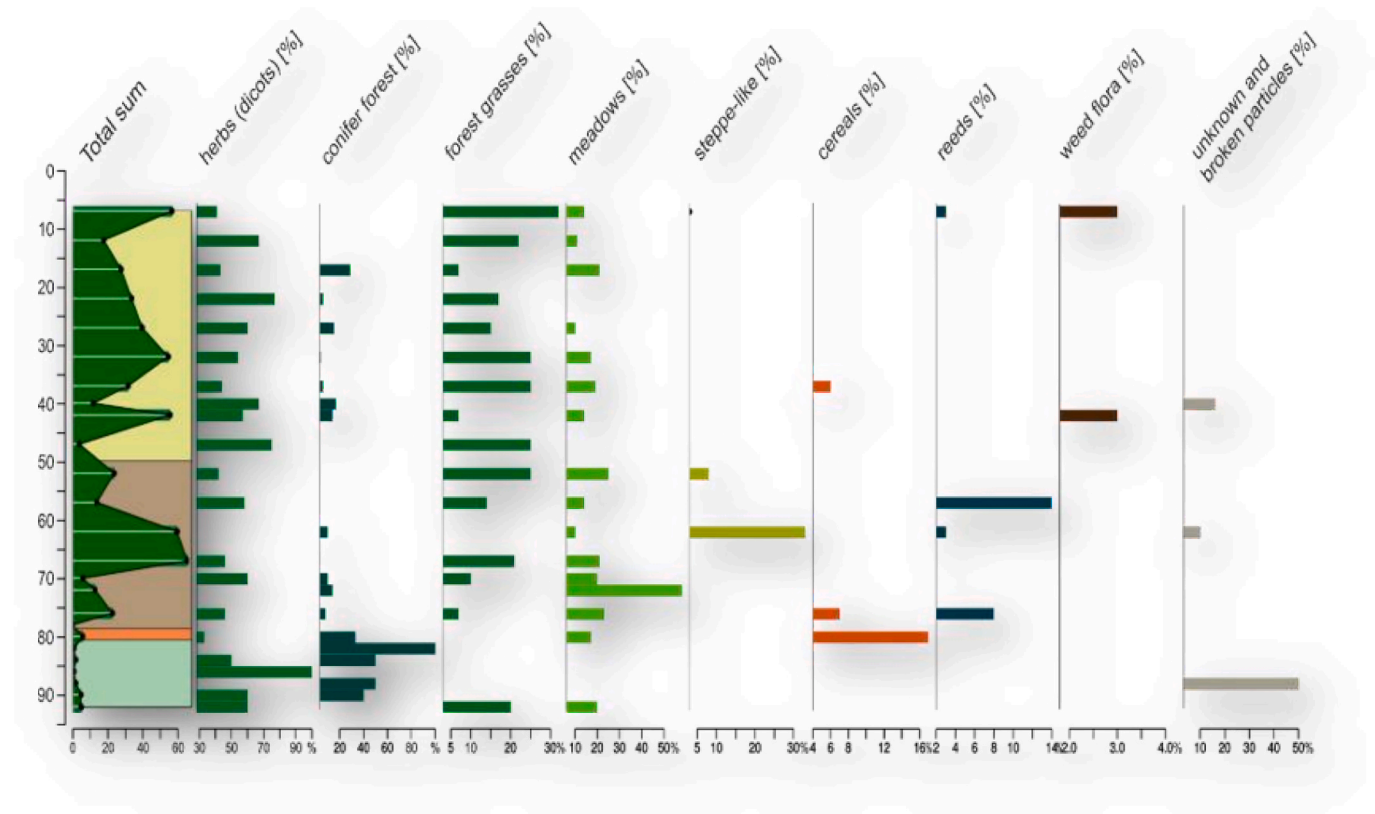


Fig. 7. Percentage of phytoliths from the OSWG1 profile.

Table 5

5 β -stanols and bile acids from the OSWGI profile. Data displayed as mean value (n = 2), standard deviation in brackets. HDCA: Hyodeoxycholic acid, DCA: Deoxycholic acid, LCA: Lithocholic acid.

Depth	5 β -stanols	Σ (epi)-5 β -stigmastanol	HDCA/DCA	DCA/LCA
[cm]	[ng g ⁻¹ sediment]			
65–70	496 (89)	399 (31)	0.20 (0.03)	11 (1.9)
70–75	446 (36)	365 (15)	0.22 (0.03)	10 (1.8)
75–80	918 (105)	735 (17)	0.20 (0.15)	20 (8.2)
80–85	158 (25)	146 (26)	0.17 (0.05)	13 (1.2)
85–90	71 (10)	62 (2.9)	0.30 (0.04)	11 (1.1)
90–95	33 (2.3)	28 (3.8)	1.0 (0.11)	26 (18)

446 $\pm$ 36 to 918 $\pm$ 105 ng g⁻¹, with Σ (epi)-5 β -stigmastanol values between 365 $\pm$ 15 and 735 $\pm$ 17 ng g⁻¹. The HDCA/DCA ratio remained stable at 0.20–0.22, while the DCA/LCA ratio increased from 10 $\pm$ 1.8 at 70–75 cm to 20 $\pm$ 8.2 at 75–80 cm. OEP values slightly decreased from 4.6 to 4.3. Σ nC26–nC35 concentrations increased from 7395 to 17,618 ng g⁻¹, whereas the (nC27 + nC29)/(nC31 + nC33) ratio remained constant at 1.7. Miliacin concentrations ranged from 530 $\pm$ 72 to 648 $\pm$ 193 ng g⁻¹, and Σ AR values ranged from 30 $\pm$ 12 to 39 $\pm$ 23 ng g⁻¹.

Unit 5 (65–70 cm) was characterized by 5 β -stanol concentrations of 496 $\pm$ 89 ng g⁻¹ and Σ (epi)-5 β -stigmastanol values of 399 $\pm$ 31 ng g⁻¹. The HDCA/DCA ratio was 0.20 $\pm$ 0.03, while the DCA/LCA ratio reached 11 $\pm$ 1.9. OEP values were low (5.0), with Σ nC26–nC35 concentrations of 8000 ng g⁻¹ and a (nC27 + nC29)/(nC31 + nC33) ratio of 1.7. Miliacin concentration was 579 $\pm$ 165 ng g⁻¹, and Σ AR amounted to 27 $\pm$ 9.6 ng g⁻¹.

5.10. Archaeology

During the profile excavations, 220 archaeological finds (both artefacts and ecofacts) were recovered from the buried soil horizon, as well as from the underlying unit, and the overlying slope deposits, including: 94 potsherds, 15 daub fragments, 5 flint flakes, and 105 animal bone fragments (Table S1).

Generally, very poorly preserved potsherd fragments from EIA were dominant, primarily in Units 3 and 4 (87 potsherd fragments in total), which stratigraphically represent the oldest anthropogenic reworked units recorded in the outcrop. Technological and cultural characteristics of this assemblage allowed to archaeologically date these units to the EIA and *Wielka Wieś* Phase. In the bottom part of Unit 5, a fragment of Early Medieval pottery from the 11th–12th century CE was found, which allowed to establish a *terminus post quem* for the beginning of slope deposit accumulation to the early Middle Ages. This corresponded with the beginning of the medieval settlement phase in OAC, which could be dated to the first quarter of the 11th century CE based on archaeological analysis and radiocarbon dating of the oldest inhumation burials. Moreover, the discovered fragments of daub likely originated from settlement waste and may have entered the profile as a result of manuring. Flint artifacts were few and not very distinctive.

5.11. Archaeozoology

Overall, 105 bone fragments of mammalian skeletal remains were

described, originating from an OSWGI trench situated in the shore zone of a kettle hole occupied from the Late Vistulian to the Middle Holocene by a small lake reservoir, subsequently transformed into a mire (Kittel et al., 2025). The remains were found primarily in the subfossil humic soil horizon (Units 3 and 4), transformed by human economic activity, and in both the underlying organic-mineral sediments (Unit 2) and the overlying slope deposits (Units 5 and 6). Most of the examined material was significantly fragmented. Only 21 fragments were identified to species or genus. The identified remains primarily represented teeth and bone fragments from mammalian skeletons. Only in the case of cattle were these larger fragments sufficient for osteometric analysis (Fig.S2).

The largest number of identified remains belonged to the domestic horse *Equus caballus*, represented only by fragments of teeth. These remains were present in slope deposits (Units 5 and 6) from the Early Middle Ages and the Modern Period. The material included 13 fragments and two complete upper right cheek teeth (M₃ and P³), belonging to adult individuals, of which 12 cheek tooth fragments came from Unit 5, dated to the Early Middle Ages. The identified cheek teeth, from Unit 5, were quite worn, indicating that they belonged to an adult individual, but not very old. Their dimensions were slightly smaller than those of domestic horse remains from other sites of this age in Poland (Piskorska, 2018). Horses have always been valuable animals due to their utilitarian value and were therefore rarely consumed. However, it cannot be ruled out that wild forms were also have been hunted (Piątkowska-Małecka, 1999).

The second most abundant species was domestic cattle (*Bos taurus*), which included a fragment of the proximal metatarsal (Unit 4, EIA) and a fragment of the right metatarsal (Unit 5, Early Middle Ages). From a fragment of the right metatarsal, discovered in a Medieval layer, several measurements were collected, including the smallest shaft width and total length, which allowed to determine that it was a female with a shoulder height of 114 cm. Based on this, it was concluded that the fragments studied belonged to short-horned cattle (*Bos taurus brachyceros*). These were typical and dominant cattle in Polish territory during Prehistory and Medieval period.

A small fragment of a premolar tooth from a domestic pig (*Sus domesticus*) was also identified in Unit 2 from Early Bronze Age. Similarly, two fragments of a metacarpal or metatarsal bone from a sheep/goat (*Ovis/Capra*) were identified in specimens from Unit 4, and from the posthole fill, which may have belonged to a single individual and were associated with the EIA. The remaining fragments belonged to unidentified artiodactyls and unidentified mammals.

Table 6

N-alkanes, miliacin and 5-n-alkylresorcinols from the OSWGI profile. Data displayed as mean value (n = 2), standard deviation in brackets. OEP: Odd-over-even predominance, Σ AR: Sum of alkylresorcinol homologues.

Depth	OEP	Σ nC ₂₆ –nC ₃₅	(nC ₂₇ + nC ₂₉)/(nC ₃₁ + nC ₃₃)	Miliacin	Σ AR
[cm]		[ng g ⁻¹ sediment]		[ng g ⁻¹ sediment]	
65–70	5.0	8000	1.7	579 (165)	27 (9.6)
70–75	4.6	7395	1.7	648 (193)	39 (23)
75–80	4.3	17,618	1.7	530 (72)	30 (12)
80–85	4.2	2635	1.7	89 (23)	16 (2.3)
85–90	3.9	930	1.4	25 (6.6)	13 (0.90)
90–95	1.5	270	1.9	24	4.2

Radiocarbon dating of bone was not possible due to their poor preservation state; the bones were extremely crumbly and lacked collagen as a result of advanced decomposition.

6. Discussion

6.1. Stages and conditions of dark soil formation

Unit 2 – Early Bronze Age (ca. 2300–1900 BCE)

Radiocarbon dating indicates that the formation of silty sands with organic mud interlamination, which constitute the parent material of the studied dark soil, occurred during the Early Bronze Age. This unit is composed of silty sand with a notable admixture of decomposed organic matter and scattered pebbles. Sedimentological analysis indicates that it consists of poorly sorted glacial silts and sands, reflecting parent material formed during the retreat of the ice sheet (Nichols, 2003; Kaiser et al., 2020). The accumulation of coarser, better-sorted deposits within the layer suggests periodic sediment transport under conditions of moderate to strong turbulence, likely associated with intensified surface runoff driven by seasonal snowmelt and/or heavy rainfall. During the final stage of slope-wash processes, finer deposits with an admixture of organic matter accumulated, probably within temporary pools on the footslope.

This is supported by micromorphological observations, which reveal a banded lamination pattern of clay and organic matter. Therefore, Unit 2 rather represents the reworked glacial parent material influenced by runoff events and groundwater level fluctuations in the shore zone of the OST1 basin (cf. Kittel et al., 2025). These features indicate changes in environmental conditions, such as temporary increases in surface water flow, which can be associated with seasonal climatic variability and/or limited human-induced disturbance during the Early Bronze Age occupation (Mycielska-Dowgiałło and Kędzia, 2011). At the same time, the intensity of runoff and sediment transport was probably increased by removal of vegetation cover caused by human activity. This allowed slope wash processes to dominate, episodically mobilizing organic-rich material downslope (Smolska, 2003; Kittel, 2015, 2016). This suggests that local deforestation alongside climatic drivers, may have been a significant factor in amplifying slope wash.

Organic matter in Unit 2 likely resulted from a combination of syndimentary deposition and postdepositional processes. The presence of banded lamination composed of clay and organic matter suggests that part of the organic content was deposited during episodic surface water flow associated with slope wash. However, the occurrence of a rounded, dark-coloured soil fragment with properties distinct from the surrounding matrix indicates additional postdepositional input, potentially derived from an overlying organic-rich horizon. Although such material could have been transported during slope processes, its lack of stratification, random orientation, and micromorphological mismatch with the host sediment suggest incorporation after deposition, possibly through bioturbation or vertical percolation.

The presence of redoximorphic features (iron-manganese nodules) and depletion zones supports periodic water saturation (Stoops et al., 2010; Golyeva et al., 2018). Further indications of moisture conditions include the presence in this unit of *Pediastrum boryanum* (Fig. 6) and Betulaceae wood remains (Jankovská & Komárek, 2013). The lack of carbonates indicates that the deposits have been subject to prolonged leaching. In the regional context, this is significant because glaciofluvial sands and gravels in the vicinity of the Ostrowite research complex commonly contain more than 10% CaCO₃ (Trzeptka & Drozd, 2005). Their absence in the studied profile suggests long-term decalcification driven by percolating precipitation water and intensive leaching of carbonate compounds.

The absence of clear signs of anthropogenic disturbance indicates that the area was extensively used without significant alteration of the soil surface. Phytolith data supplement the palynological record by indicating a diverse flora typical for open and semi-open habitats,

suggesting that these grazed areas formed part of a mosaic landscape of open patches and forest edges typical of swamp margins (Gill, 2012). Vegetation biomarkers (*n*-alkanes) further confirm the predominance of terrestrial vegetation developing outside zones of permanent water-logging but under humid conditions.

Unit 3- Bronze Age to Early Iron Age (from ca. 1900 BCE to 800–600 BCE).

Unit 3 represents a buried humic soil horizon that has formed on the surface of Unit 2. Consisting of light brown silty sands with humic admixtures, it is comparatively thin, likely due to compaction and later anthropogenic disturbance.

Sedimentological parameters suggest relatively homogeneous depositional conditions, supporting the interpretation that Unit 3 is of *in-situ* origin. The gradual transition between Units 2 and 3, which is visible both macroscopically and microscopically, together with the homogeneous groundmass, supports the interpretation of natural and weakly disturbed soil formation (McLaren, 1981).

Palynological record indicated very low content of microfossils what may suggest high disintegration of organic matter, possibly due to at least temporal aeration of the sediments. Sporadically noted spores of Polypodiaceae and remains of wood cells of Betulaceae suggest local tree vegetation with ferns and the morphology of the wood cells may indicate *Betula* thickets rather than *Alnus* stands. At the same time, the presence of *Rivularia* and spherical microfossils of algal origin indicates relatively wet habitat conditions, which likely promoted *in situ* preservation and accumulation of organic matter within the sediment.

Unit 4 – Early Iron Age (ca. 800–600 BCE)

Radiocarbon dating indicates that the formation of this layer occurred during the Early Iron Age, most probably in the 8th century BCE.

A distinct and sharp lithological discontinuity clearly marks the transition between Units 3 and 4, observable both macroscopically in the outcrop and microscopically. From a sedimentological perspective, these two units differ considerably regarding their main grain sizes: Unit 3 is dominated by sandy and Unit 4 by silty sediments. This shift in sedimentary characteristics suggests alternating slope processes at the transition of both horizons, indicating that this unit may not be an *in-situ* soil horizon, but rather a slope deposit accumulated prior to, and was later transformed by, anthropogenic reworking. Golyeva et al. (2018), Sikora et al. (2019), and Mikhaylova et al. (2025) have documented similar lithological discontinuities and anthropogenically disturbed stratigraphy, identifying similar features in disturbed archaeological layers.

Elevated Fe/Mn and Fe/S ratios indicate mobilization of Fe and S under reducing conditions. These redox-sensitive elements are often present as colloids, which affect soil nutrient availability (Schaller et al. 1997; Korzeniowski et al. 2020).

This horizon is characterized by the highest proportion of Betulaceae wood cells and a relatively abundant presence of ferns from the Polypodiaceae family. Pine is regularly noted in pollen data.

Micromorphological features provide additional insights into land use practices recorded in this unit. The abundance of interconnected channels and chambers indicates active bioturbation by roots and soil fauna (e.g., insects, earthworms). This suggests well-aerated conditions and efficient water movement which are characteristics of biologically active, organically enriched topsoils. This high biological activity promoted the development of granular, blocky, and crumb microstructures. Tillage likely contributed to increased porosity and the formation of channel voids, while repeated manuring likely enhanced structural complexity, resulting in a porous blocky–crumb microstructure although not directly observed in micromorphological record (Stoops and Marcelino, 2018). Similar micromorphological signatures were observed in EIA buried soils beneath barrows. Mikhaylova et al. (2025) reported that the organic-rich horizons contained dominant subangular blocky and granular structures, which transitioned to intergrain microaggregate structures in the deeper less biologically active layers.

Therefore, the formation history of the buried soil represents a long-term transition from natural to anthropogenically modified soils. The parent material of glaciofluvial sands (Unit 2) shows minimal evidence of human disturbance and is characterised by features typical of humid mosaic landscapes near wetlands. Unit 3 represents a naturally developed soil horizon formed through gradual accumulation of organic matter and pedogenic transformation of the underlying sediments, with only minor post-depositional disturbance. Anthropogenic reworking during the EIA strongly overprinted natural processes in Unit 4.

6.2. Reconstruction of past human-environmental interactions and economic activity

6.2.1. Traces of forest clearance and fertilization during EIA

During the EIA in N Poland, significant changes occurred in the vegetation, often driven by slash-and-burn practices aimed at creating open areas for cultivation and grazing (Arroyo-Kalin, 2012; Szal et al., 2014; Krupski et al., 2022). Evidence from the Ostrowite sequence suggests that fire played a central role in this process. Charred fragments of *Alnus*, *Quercus*, and other deciduous taxa found in the buried layer indicate local burning, likely linked to forest clearance for cultivation in the immediate vicinity of the site, or waste area with the remains of fuel wood use. This is supported by the pollen spectrum in the anthropogenically reworked horizon (Unit 4): light-demanding trees and shrubs are dominating, alongside taxa from wet habitats and a few shade-tolerant species. A marked decline in *Alnus* suggests deliberate removal, possibly due to its nitrogen-fixing properties, which made it suitable for slash-and-burn strategies (Saarse et al., 2010; Bonk et al., 2024). An elevated concentration of Betulaceae wood cells further supports the hypothesis of intensified burning and forest clearance during this period. This is supported by a predominance of *n*-alkanes from deciduous forest vegetation (nC_{27} , nC_{29}) over grass-derived *n*-alkanes (nC_{31} , nC_{33}). Comparable vegetation shifts have been observed at other Iron Age sites in N Poland (Miotk-Szpiganowicz, 1992; Taras & Krystyna, 2012; Wacnik et al., 2014).

These vegetational shifts are accompanied by changes in soil geochemistry. Elevated concentrations of Mn and Fe indicate an increased input of minerogenic material from overland flow, which is linked to the canopy removal and soil erosion (Szal et al., 2014; Bonk et al., 2024). These chemical signatures are accompanied by an increase in the remains of algal and cyanobacterial remains – organisms that thrive in eutrophic conditions – suggesting intensified human impact on the catchment area. This geochemical and biological pattern is consistent with observations of anthropogenically modified soils at other archaeological sites in N Poland and beyond (Wilson et al., 2008; Bobrovsky et al., 2025).

Macroscopic finds within Unit 4, including potsherds, daub fragments, and faunal remains, coincide with elevated levels of P, S, Zn, TOC, and N. This geochemical and material assemblage suggests the deposition of domestic waste – possibly including manure – which may reflect either intentional fertilization or general refuse disposal contributing to localized enrichment in soils (Fiedler et al., 2025). While no microscopic remains of dung were observed in thin sections, this absence may reflect rapid decomposition in open-air conditions, sporadic application, or post-depositional disturbance through cultivation (Bogaard et al., 2013). Similar fertilization strategies are documented in Celtic fields of NW Europe, where household debris and animal waste were co-deposited, forming mixed anthropogenic horizons rich in ceramics and nutrients (Arnoldussen & van der Linden, 2017; Sikora et al., 2019).

6.2.2. Arable farming and livestock breeding during EIA

The presence of cereal phytoliths in Unit 4 indicates that crop cultivation took place at OAC during the EIA. Although too degraded to be assigned to specific cereal species, their occurrence within a buried anthropogenic layer constitutes an important indicator of a former

cultivation surface (Golyeva et al., 2018). This is further supported by micromorphological features, such as granular and crumb microstructures, an abundance of biogenic channels, and high porosity, indicating repeated tillage and soil amendment through organic inputs (Nicosia & Stoops, 2017; Stoops, 2021).

These findings are further supported by considerable amounts of miliacin, a biomarker used for the reconstruction of broomcorn millet (*Panicum miliaceum*) cultivation, alongside ARs that are enriched in different whole grain wheat species (e.g., einkorn, emmer, barley, spelt and rye) (Hammann et al., 2019). This indicates a mixed cropping system at the OAC consisting of different cereals encompassing einkorn, emmer, spelt and barley next to broomcorn millet. This cereal inventory was typical for EIA societies in Europe (Salova et al., 2024). Comparable miliacin concentrations (up to 350 ng/g) were detected in soils from NE France, which were sampled from Bronze Age and Iron Age cereal pits (Courel et al., 2017). However, also distinctly lower levels of miliacin (up to 15 ng/g) from Ukrainian paleosols were interpreted as indicators for millet cultivation (Motuzaite-Matuzeviciute et al., 2016), while such high concentrations of miliacin as detected in the OSWGI profile, are more common in lacustrine sediments, where weathering and microbial turnover are reduced (Jacob et al., 2008; Dubois & Jacob, 2016). In contrast, studies on AR recovery from soils and sediments are rare (Scherer et al., 2025), even though these biomarkers are frequently recovered from archaeological pottery in the context of organic residue analysis (Hammann et al., 2022; Colonese et al., 2017). In conjunction with the phytolith and pollen record, we suggest that the cultivation of broomcorn millet alongside wheat species played a decisive role for the EIA farmers at the OAC.

As a C₄ plant, broomcorn millet is advantaged in warmer and drier climate, produces higher yields in shorter growing periods (60–90 days) and is suitable for long-term storage. In areas with summer rainfall, the cultivation of millet does not require irrigation and only minimum tillage and manure application is needed before seeding (Dal Corso et al., 2022; Taylor et al., 2020). This made the cereal ideal for extending the range of staple crops of past agricultural systems that have been often based on C₃ cereals such as wheat and barley (Standall et al., 2025). These results align with broader regional evidence of agricultural intensification during the Hallstatt Period, as postulated by Łuka (1975) and Ostojka-Zagórski (1982). They observed an increasing focus on cereal production, which was facilitated by ploughing. Kmiecinski (1990) attributed traces of plowing at the Odry site to the agricultural activities of the PC. Meanwhile, the discovery of a colter at Lisia Jama and of sickles in the Pomeranian region (Łuka, 1975) further highlights the technological means used for cultivation at this time; notably, a bronze sickle from Ostrowite, though found in a secondary context within the fill of a Roman Period feature, also adds to this evidence. Similarly, palynological studies by Miotk-Szpiganowicz (1992) confirmed the presence of cultivated fields and pastures in the Tuchola Forest Region during the Late Bronze Age to Middle La Tène period. According to Dziegielewski and Przybyła (2024), agriculture formed the economic foundation of Bronze and Early Iron Age communities in Pomerania, where cereal cultivation, especially wheat, barley, millet, and spelt played a central role. Archaeobotanical finds from the Juszkowo site near Gdańsk, including cereal impressions on pottery and charred grains of wheat, rye, barley, and millet (Klichowska, 1962, 1972, 1979; Podgórski, 1979), further substantiate the significance of cereal cultivation among PC populations.

Beyond the evidence for cereal cultivation, the keeping of livestock (Vázquez et al., 2021; Zocatelli et al., 2017) and application of organic manure to maintain adequate conditions of agricultural soils (Lauer et al., 2014) were likely important for past subsistence economies. Coarse mineral infillings observed in the thin sections for buried soil Unit 3 most likely originated from overlying layers and were introduced by human activities such as uprooting or episodic rainwater infiltration (Stoops et al., 2010). Archaeological evidence from these layers revealed high concentrations of bone fragments, potsherds, and daub,

corresponding with elevated phosphorus concentrations.

At the OAC, traces of past fecal inputs were identified through the analysis of 5 β -stanols and bile acids, indicating high proportions of ruminant faeces in the EIA soil horizons. Based on the bile acid spectra, this fecal input most probably originated from cattle, goat and sheep (Prost et al., 2017). In addition, excavations yielded several highly fragmented mammalian long bones, including two horse teeth and a fragment that was identified as belonging to an ungulate.

Approximately 50 identifiable bone fragments were recovered from Unit 4. These include pieces of skull, as well as long bones such as metacarpals, metatarsals, and radial bones. Most of the remains belong to medium- to large-sized mammals, with several fragments attributable to domestic species such as cattle (*Bos taurus*) and possibly sheep or goat (*Ovis/Capra*), suggesting the presence of domesticated animals and indicating animal husbandry at the site. This interpretation is further supported by palynological analyses of the same unit, which revealed fungal spores commonly associated with dung, serving as indirect indicators of pastoral activity (Szal et al., 2014; Kołaczek et al., 2025). Only a few fragments of domestic pig (*Sus domesticus*) were identified in the lower part of Unit 3. Notably, no pig residues were recovered from the buried anthropogenic level, which may indicate that pigs were either consumed less frequently or kept aside from cattle. This absence is also evidenced in biomarker data, suggesting that pigs might not be grazed in the vicinity of the OSWG1 area. Luka (1974) argued that continuous field rotation was not conducive to pig farming, which may explain the lower frequency of pig remains (cf. Kittel, 2005).

The initial results of the archaeozoological analysis of the bones found in stratigraphic units dated to the EIA, show that cattle formed the majority of the livestock group. Cattle bones were even found in the fill of a cremation grave pit. Bones of pigs, goats or sheep were also discovered, as well as a single horse bone. The presence of wild boar was confirmed among the hunting animals. An auroch bone was found, although its classification remains uncertain due to its poor preservation. In the fill of a cremation grave of PC people uncovered at OAC, a *Valvata piscinalis* shell and remains of pike (*Esox lucius*) were also identified (personal communication of D. Makowiecki).

Taking together the different lines of evidence, the presence of livestock, especially ruminants, is likely for the OAC and domestication practices were part of the Pomeranian subsistence economy at this site. However, based on the given data, a differentiation between intentional manuring of agricultural soils and unintentional fecal inputs as part of pastoral activities on fallow land is not possible. Some authors emphasize that livestock breeding played a dominant role in the economy of the PC in N Poland, as indicated by the prevalence of cattle and sheep/goat bones in the faunal assemblages (cf. Sobociński 1972; Ostoja-Zagórski 1982; Kmiecinski 1990). Evidence recovered during the excavations of the OSWG1 sequence suggests an integrated agropastoral system. This interpretation could be supported by the discovery of a posthole, together with bone and pottery fragments. The posthole may represent the remains of structures related to gardening or fencing, connected to settlement activities. This context could point to the use of a fallow-rotation cultivation system (Bogaard et al., 2013), whereby fields were divided into several plots to allow for the alternating cultivation of crop and grazing.

Altogether, this anthropogenic layer shows the presence of cereal phytoliths, confirming the cultivation of crops alongside the keeping of livestock, particularly cattle, indicating that both arable farming and animal husbandry were practiced simultaneously at the site. Beyond the interpretation of the site itself, the results have wider significance for the archaeology of the region. The excavations provide new and well-preserved stratigraphic evidence of human activity that is still relatively uncommon in this part of the Baltic region. As such, the findings represent an important addition to the archaeological record and contribute to a better understanding how prehistoric settlers in the Baltic region shaped the environment to sustain their subsistence. Furthermore, the results highlight the potential of a multi-proxy

approach for investigating complex archaeological sequences. The application of similar integrated methodologies at other sites may facilitate the identification of anthropogenic deposits and contribute to a more comprehensive reconstruction of prehistoric settlement dynamics, land-use practices, and human–environment interactions.

7. Conclusions

A strongly anthropogenically reworked buried soil, covered by slope deposits, was identified at the OAC site. Geochronological analyses indicate that its formation occurred during the EIA and was likely associated with settlement activity of the PC during the *Wielka Wieś* Phase of the Hallstatt C period (8th–7th centuries BC).

The reconstruction of the buried soil sequence demonstrates a long-term transition from natural to increasingly anthropogenically modified conditions. The lowermost horizon (Unit 2) shows minimal evidence of human disturbance, whereas the overlying Unit 3 represents a humic horizon formed through gradual accumulation of organic matter and soil development under relatively stable conditions. In contrast, Unit 4 exhibits clear signs of intensive anthropogenic reworking, most likely linked to mixed farming practices during the EIA.

- (i) During this period, forest clearance intensified and became an integral part of land-use strategies. Fire was likely used to manage vegetation and modify forest structure, facilitating the expansion of settlements and agricultural areas. This is reflected in the decline of deciduous tree taxa and the simultaneous increase in grassland indicators. These changes in vegetation cover likely reduced slope stability and enhanced surface runoff, leading to increased erosion and the accumulation of colluvial deposits during the EIA.
- (ii) Land use appears to have followed a shifting system, in which areas were cultivated for crop farming, and subsequently used as pasture after harvesting. Such multifunctional use of space contributed to enhanced soil fertility, allowing for prolonged and intensive land use. Cereal phytoliths and the presence of miliacin demonstrate the cultivation of broomcorn millet alongside other cereal crops. The presence of cattle and the input of dung was an integral part of this agro-pastoral system, as evidenced by faecal lipid biomarkers and archaeozoological evidence. The interdisciplinary approach used in this study deepens our understanding of prehistoric land use dynamics in the Baltic region, going beyond the local archaeological record.

CRediT authorship contribution statement

Margarita Zalinian: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Piotr Kittel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Karolina Leszczyńska:** Writing – review & editing, Supervision, Software, Resources, Investigation, Data curation. **Sabine Fiedler:** Writing – review & editing, Validation, Resources, Data curation. **Annemarie Susanne Bach:** Validation, Methodology, Formal analysis, Data curation. **Jerzy Sikora:** Writing – review & editing, Software, Resources, Methodology, Formal analysis, Data curation. **Renata Stachowicz-Rybka:** Writing – review & editing, Software, Resources, Methodology, Formal analysis, Data curation. **Magdalena Moskal-del Hoyo:** Writing – review & editing, Software, Resources, Methodology, Formal analysis, Data curation. **Alexandra Golyeva:** Writing – review & editing, Software, Resources, Methodology, Formal analysis, Data curation. **Miroslaw Makohonienko:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Daniel Okupny:** Writing – review & editing, Visualization, Software, Resources, Methodology, Data curation. **Marek Krapiec:** Writing – review & editing, Software, Resources,

Formal analysis, Data curation. **Artur Ginter:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Wojciech Tołoczko:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Krzysztof Stefaniak:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Karol Witkowski:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Grzegorz Poręba:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Sascha Scherer:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Margarita Zalinian reports financial support was provided by University of Lodz. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2026.117902>.

Data availability

Data will be made available on request.

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